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FLEXIBLE SYNTHETIC LINERS AND THEIR USE IN LIQUID WASTE IMPOUNDMENTS

Alberta
ENVIRONMENT

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6105009

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ABSTRACT

The use of flexible synthetic material as pond liners is rapidly gaining popularity. If properly designed, ponds with flexible liners can be extremely effective in minimizing seepage. In some instances flexible liners have been recommended for use instead of natural liners and in conjunction with natural liners.

Selection of a flexible pond liner depends upon the conditions under which the liner will be utilized. The primary consideration is the compatibility between the chemical waste and the liner. The degree of seepage through a properly selected flexible liner material is primarily dependent upon subgrade preparation and liner installation. The tolerable level of seepage is dependent upon site location and the nature of the potential pollutant.

Flexible liner fabrication, seaming, reinforcement, testing and failure mechanisms are examined in this report. In addition, some of the commonly available flexible liners are examined with respect to their physical/chemical characteristics.

Since proper performance of a selected flexible liner is dependent upon pond design and construction, the report also presents an overview of engineering design considerations for liquid waste impoundments, lined with a flexible liner.

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1. INTRODUCTION

The use of ponds or lagoons for the containment of liquids for the purposes of storage, recycling, treatment or disposal (evaporation) is standard practice for many industries.

In many situations the traditional pond liners or so-called "rigid" liners such as concrete, asphalt, metals and clay, have proven unsatisfactory in minimizing seepage. These liners which (under certain circumstances) inadequately control seepage, are being replaced or supplemented with flexible synthetic liners or "flexible" liners (the terminology to be used throughout this text). Spray-on synthetic liners will not be discussed in this text due to the limited information and experience with this type of liner for liquid waste impoundments.

The ideal pond liner should be (Stewart, 1978):

1. impermeable to the intended waste;
2. durable;
3. flexible over a wide range of temperatures;
4. resistant to weathering and to chemical, biological, and mechanical damage;
5. easy to install; and
6. economical.

A totally impermeable membrane which can meet all of the above mentioned characteristics has not been developed and therefore a compromise between liner characteristics and liquid containment requirements is required. Factors to be considered in such a compromise include:

1. the chemical composition and concentration of the intended waste or wastes (liner/waste compatibility);
2. site characteristics - soil/geology
   - vegetation
   - surface and groundwater hydrology
   - meteorology
   - topography;

3. environmental guidelines - leakage tolerances (waste and site specific)
4. economics.

Liner/waste compatibility is the most controllable factor in that liner characteristics can be altered through the compounding process in the manufacturing of the liner. This process involves mixing various chemical compounds with the base polymer resin in order to create a liner with specific properties. Through this process all other factors could be accommodated to some degree in order to obtain the best liner for a given application.

Flexible liners can be designed to contain a wide variety of fluids with minimal seepage. In addition, the installation and maintenance of a flexible liner can often be achieved with relative ease and economy. However, flexible liners, as with any material, do have their disadvantages; some of these disadvantages are:

1. the relative vulnerability of some liners to ozone and ultraviolet (UV) radiation;
2. the limited ability to withstand mechanical stresses;
3. susceptability to laceration, abrasion and puncture; and
4. the tendency of thermoplastic materials to crack and crease at very low temperatures and stretch and distort at very high temperatures.

This report reviews various commercially available flexible liners in terms of their physical and chemical properties and presents general subgrade preparation and liner installation considerations which are integral aspects of the successful application of flexible liners.

2. FLEXIBLE LINER INDUSTRY

2.1 RAW MATERIALS AND CLASSIFICATION

A flexible liner is made from raw polymer combined with ingredients such as carbon black, pigments, accelerators, stabilizers, antioxidants, and plasticizers where necessary.

The raw polymer is based upon one or two of a number of monomers, depending upon the desired liner characteristics. The monomer is a repeating molecular unit from which the polymer is formed. Monomers are joined together through the process of polymerization. Many combinations and variations of polymers can be manufactured. Some of the most common polymers used in the liner industry are:

1. polyvinyl chloride (PVC)
2. polyethylene (PE)
3. neoprene (polymer of chloroprene)
4. chlorinated polyethylene (CPE)
5. chlorosulfonated polyethylene (Hypalon)
6. polymer of ethylene-propylene diene monomer (EPDM)
7. polymer of isoprene and isobutylene (butyl rubber)

All polymers can be classed as either rubber or plastic. Rubber (or elastomer) is a polymer material which is capable of deformation and elastic recovery; these include butyl rubber, EPDM and neoprene from the above list. Plastic is a polymer material which can be formed or molded under heat and pressure in its raw state and trimmed and finished in its hardened state; these include PVC, PE, and CPE from the above list. Hypalon is a unique material which can be classed as either a rubber or a plastic depending on its age.

Through the process of compounding, polymer characteristics can be altered such that they can be repeatedly softened and hardened; this type of material is termed a "thermoplastic". Most flexible liners are supplied as a thermoplastic (this allows for easier seaming).

Prior to the use of rubbers or elastomers they are most often cured or vulcanized. Vulcanization is a physiochemical change which results from the crosslinking of rubber polymers through the use of sulphur (typically), accelerators and metallic oxides (usually zinc). The resulting material becomes less plastic and elastic properties are maintained, improved or extended over a greater temperature range. The cured material is very stable and has few or no available "sites" with which to link other molecules; thus seaming is a difficult task.

2.2 MANUFACTURING

Manufacturers formulate, compound and form sheets of the flexible liner material and it is the manufacturers' expertise in these areas that controls the properties of the finished product (U.S. EPA, 1980).

The first step in the manufacturing process involves mixing or compounding raw polymer with various ingredients. Of the additives, plasticizers are among the most important in determining a liner's behaviour. Plasticizers increase a polymer's workability, flexibility or extensibility. Plasticizers are most widely used with PVC where the choice of plasticizer determines the conditions under which the liner may be used.

Other ingredients may or may not be added depending on the required qualities. For example, light stabilizers are used to inhibit ultraviolet damage, pigments are used to impart colour, heat stabilizers are used to counteract solar radiation and high processing temperatures and extenders are used to reduce costs.

When carbon black of proper particle size and shape is added to rubber-like materials, it has the ability to improve the liner. Within rather broad limits, the more carbon black added, the stronger and better the overall properties of the membrane. Carbon black has the tendency to enhance the best inherent properties of the rubber.

Following the compounding process, the material is converted into sheets or rolls by one of two basic methods: calendering or extrusion. Calendering is used in forming reinforced (supported) and non-reinforced (unsupported) polymer sheeting, whereas extrusion is only used in preparing non-reinforced polymer sheeting.

Calendering is the most common method of the two. It involves passing heated polymer through a series of three or more heated rollers to form a sheet of predetermined thickness. Unsupported liners are typically manufactured in multiple plies; this minimizes pinholes in the liner. When producing a supported liner, reinforcing fabric is placed between the plies of the polymer sheets. Typically a compounded polymer is calendered into sheets 1.2 to 1.8 meters wide and about 100 meters long (Fisher, 1976).

The extrusion method involves producing a tube or cylinder of polymer which is then slit to the desired thickness. For thicker gauge materials, thick sheets are extruded directly. This method is used primarily with polyolefins such as polyethylene.

2.2.1 Liner Reinforcement

Liners are reinforced or supported primarily to (1) improve dimensional stability (for example, unsupported hypalon can shrink up to 30-40% whereas a supported hypalon may only shrink by 2%); (2) increase puncture resistance (positively correlated with an increase in tensile strength); and (3) increase tear resistance. Supported liners also minimize creep (liner movement down a slope) and tend to increase ozone resistance through the minimization of elongation since elongation accelerates ozone cracking and deterioration of ozone sensitive liners. Reinforcement also increases the tensile strength provided that the scrim (reinforcing fabric) has a greater tensile strength than the liner itself. A listing of reinforced liners, their physical properties and the types of scrims used is presented by Ewald (1973).

A flexible liner is reinforced by the use of a scrim. Scrims are open weave mesh fabrics and are specified in terms of count and denier. Count refers to the number of filling (widthwise) yarns, and warp (lengthwise) yarns per square inch. Denier is a unit of fineness of a yarn weighing 1 gram for each 9000 meters. Deniers are usually specified in multiples of 110, 210, 420, 840 and 1000 (Lee, 1974).

Scrims of a high count and denier are often referred to as densely woven fabrics. In Figure 2.1, if the denier is 210 and the fabric is nylon, the correct designation of the scrim would be 11 x 11, 210 denier nylon.

Nylon, polyester and polypropylene are the most commonly used reinforcing fabrics. Table 2.1, outlines the advantages and disadvantages of these common reinforcing fabrics. Cotton, jute and glass fabrics have been used, however, they have been found to be water sensitive and susceptible to attack by soil microbes. Cotton, while it has good sun aging qualities, cannot resist microbial attack even with a protective coating. Reinforcement construction using cotton, usually loses most of its strength in less than five years (Kays, 1977).

A supported liner is manufactured in the calendering process, whereby a scrim is introduced between individual plies of liner

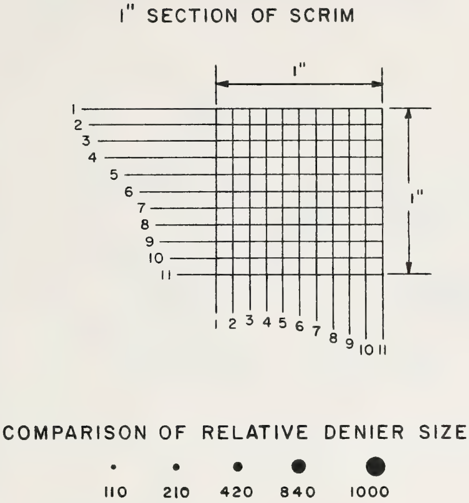


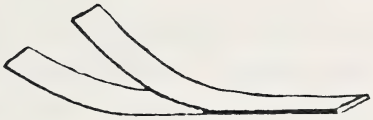
Figure 2.1 Scrim and denier designation (Lee, 1974).

material (see Figure 2.2). Prior to lamination the scrim may be heat-set or dipped into a latex solution in order to (1) keep the scrim from distorting; (2) act as a tie-coat between membrane and fabric; (3) prevent direct membrane fabric bond (this optimises tear strength); and (4) heat stabilize the fabric.

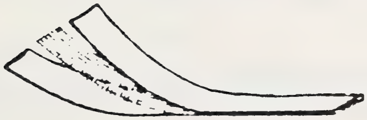
Proper adhesion of the liner plies and the reinforcing scrim is achieved by means of a process called "strike through", in which the liner material is forced through the openings in the scrim weave towards the other layer of liner material. The problem of delamination is drastically reduced by this process. To enhance strike through, some manufacturers are turning to heavier scrims with lesser counts, which provide larger weave openings. This improves the quality of the liner because tear resistance and ply adhesion (as opposed to tensile strength) are considered the important parameters in reinforced lining technology.

TABLE 2.1 Reinforcing Fabrics; advantages and disadvantages.

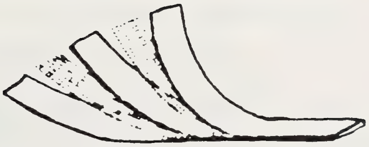
Fibre	Advantages	Disadvantages
Nylon	- Is an excellent reinforcer with a high strength to weight ratio. - Is alkali resistant. - It is readily available and is resistant to water and soil organisms.	- It is not very acid resistant. If acid is wicked into contact with fibres, depending on the type, concentration and temperature of the acid, it can destroy the scrim in a matter of a few months. - Deteriorates fairly quickly in sunlight, rate of deterioration depends on the weight of the fabric and the colour and thickness of the liner materials. White and pastel coatings less than 10 mil thick allow too much ultraviolet light to pass through causing losses in physical properties. Coating with a black or dark pigmented film helps. - No adhesive qualities towards the liner materials.
Polyester (Dacron)	- Tends to last longer than nylon under similar conditions (but there is insufficient information to allow for meaningful predictions). - Good acid and sunlight resistance. - Better shrinkage resistance than nylon. - Better resistance to a broader range of chemicals than nylon.	- It is not quite as strong as nylon and constructions of equal strength are more costly. - No adhesive qualities towards the liner materials.
Polypropylene	- Almost universally resistant to both acids and alkali.	- Has poor resistance to sunlight and must be pigmented. - Still in its experimental stage.



Unreinforced



3 Ply



5 Ply

Figure 2.2 Typical membrane construction. Top is unsupported elastomer consisting of 2 plys of sheet stock. Centre and bottom diagrams show 3-ply and 5-ply supported constructions. Open weave scrim is encapsulated between layers of elastomeric sheet (Fisher, 1976).

In order to control the problem of wicking (liquid absorption by the fabric) it is important that a liner's edges be encapsulated (whereby the scrim is terminated 1 to 1/8 inch from the liner's edges).

2.3 FABRICATION

After the sheets have been manufactured they are ready for fabrication into panels. Panels are formed by joining or seaming the sheets or rolls. Panel sizes vary depending on job application and are generally a function of weight and the ability of the crew to place it in the field.

2.3.1 Seaming Methods

The best lining system is only as good as its weakest seam. In choosing the correct liner for a given situation, due consideration must therefore be given to the seaming techniques to be used both in the field and in the fabricating plant. The primary factors in determining the method to be used for a successful field and factory seam are whether a liner is cured or uncured and the compounding recipe of the liner. To determine the exact procedures and materials needed to seam a particular liner, the manufacturer or a qualified installer should be consulted.

Factory seams are usually more reliable than field seams, since they are made under controlled conditions. Therefore, it is generally advantageous to try to optimize the number of factory seams. Figure 2.3 show a typical factory and field seam.

In the case of supported liners, it is general practice for fabricators to insist that the selvage edge does not exceed 1/4 of an inch from the scrim (Mooney, 1982). The objective is to optimize the seaming of a supported portion of one sheet to the supported portion of another sheet. This is due to the fact that

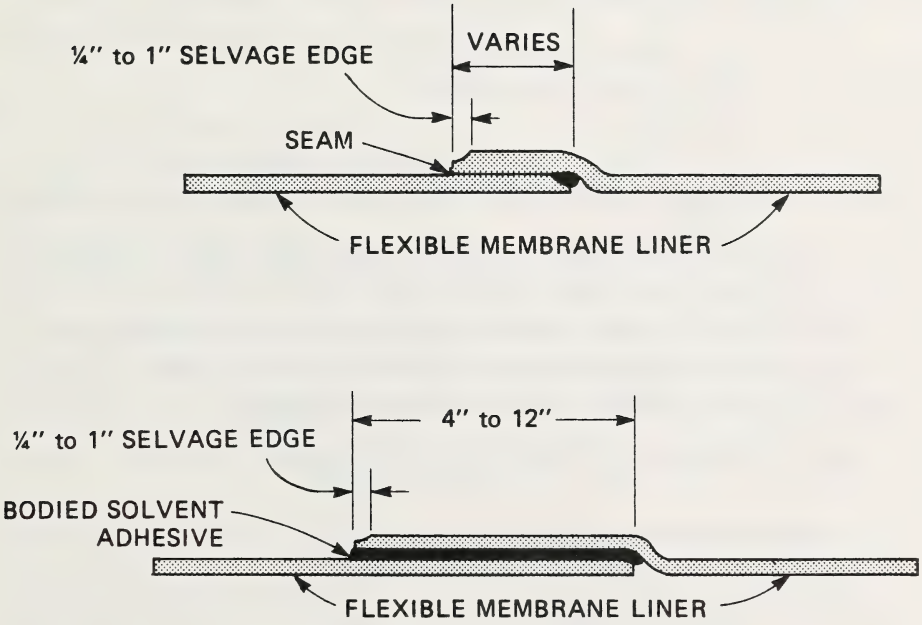


Figure 2.3 Typical factory (top) and field (bottom) seams (U.S. EPA, 1980).

often manufacturers will alter the formulation of supported liners to improve chemical resistance, at the expense of polymer strength. Therefore, bonding an unsupported portion of one liner to a supported or unsupported portion of another liner may result in a weak (low strength) seam.

The success or failure of the liner installation often depends heavily on the installing contractor's ability to reliably field seam. Factors on site which may influence the field seaming operation include (Kirby, 1979):

1. the ambient temperature;
2. the relative humidity;
3. the wind;
4. the effect of clouds on liner temperature;
5. the moisture content of the subsurface beneath the liner;
6. the supporting surface on which the seam is bonded;
7. the experience of the crew;
8. the quality and consistency of solvent or adhesive;
9. the cleanliness of the seam interface; and
10. the quality of the seaming equipment.

There are five basic methods of seaming:

1. Dielectric;
2. Thermal;
3. Extrusion Welding;
4. Solvent; and
5. Adhesive.

2.3.1.1 Dielectric Seaming

This method is based on the transmission of a high wattage radio frequency signal, through the material to be seamed. A source of 10 to 23 kilowatts is required. Enough heat is generated within 2 to 5 seconds to cause the material to flow together at the interface to produce a homogeneous seam. Close control of heat pressure and dwell time are necessary. This is predominantly a factory process.

This seaming method can produce the strongest seam on a variety of unreinforced materials. However, it is also the most expensive method of fabricating and the tensile strength of reinforced material may be reduced as much as 20% (Kirby, 1979).

Electronically bondable films should not contain conducting carbon black, metallic dispersions or metallic printing inks and certain other inorganic substances are restricted as to type and quantity (Kays, 1977). The manufacturing plant must always be informed if seaming is to be done dielectrically so that proper manufacturing precautions are taken.

2.3.1.2 Thermal Seaming

This method utilizes a combination of heat and pressure to render the material thermoplastic, causing it to flow together at the interface. This can be done by direct contact of heated elements or with the use of a heat gun. Heat seaming is limited by material thickness. For example, Hypalon sheets thicker than 1.1 mm (45 mils) are not conducive to thermal seaming. Again, close control of heat, pressure and dwell time are necessary.

This method results in a good strong bond and is inexpensive. However, material degradation and loss of scrim strength (on that portion adjacent to the seam) can result due to excess pressure and heat. This is predominantly a factory process. Heat dissipation, availability of power and various weather conditions are distinct disadvantages of using this method in the field.

2.3.1.3 Extrusion Welding

Extrusion welding involves applying a bead of extrudate (molten polymer which has been forced through a die) on each edge of the overlaped sheets (top and bottom) or in the seam interface and pressure applied with rollers to insure complete surface contact. When the bead is applied to each edge, often gummed tape or some other adhesive is used to hold the sheet in position during welding. The extrudate material is of the same compounded polymer as the material being seamed. The temperature of the extrudate is critical to insure a proper bond, therefore the extruder (the device which forms the bead) must have good temperature controls.

Extrusion welding systems are becoming more popular in the field and create the most reliable field joints currently available (Kirby, 1979). To date extrusion welding is most commonly used for HDPE liners.

2.3.1.4 Solvent Seaming

In this method solvents are used to partially dissolve the liner interface. Upon evaporation of the solvent and with pressure and dwell time a bond is then formed. External heat may be applied to speed this process and to increase seam strength.

This is the least expensive method of seaming and is relatively rapid. The problems inherent with solvent seaming are seam "holidays" which are created due to breaks in solvent feed, and degradation of the liner and/or scrim due to the use of too much or a too powerful a solvent. The precise amount of solvent is critical in establishing a good seam, therefore, the fabricator's experience is very important in the use of this system.

2.3.1.5 Adhesive Seaming

There are several types of adhesive systems employed for both factory and field seaming, of which the two-part epoxy cements, the one component cold-setting adhesive, and systems based on the use of gummed tapes are the more prominent. These systems, along with solvent systems must be considered for all cured materials since they cannot be seamed by heating methods.

2.4 TESTING

The National Sanitation Foundation (NSF, 1983) has established standard tests and minimum quality standards for flexible membrane liners used for the containment of contaminated liquids or chemicals. The tests required and the corresponding standards for each flexible liner material may vary depending upon the principle of its design and/or formulation. Specific ASTM standard test methods have been selected for each property and for each liner material.

Table 2.2 is a comprehensive list of the properties that are to be tested. As can be seen from Table 2.2 both the liner material and the factory seam must be tested.

It is important to realize that liner characteristics can vary drastically from one batch to the next for a given base polymer. Variations may be attributed to one or all of the following factors:

1. variations in the base polymer resin;
2. compounding variations;
3. variations in techniques and equipment used in sheet formation; and
4. variations in the reinforcing fabric.

TABLE 2.2 Flexible Liner Material Properties for which the NSF has Established Standard Tests and Quality Standards. (The specific properties to be tested, the corresponding standard test method and the standard for various liner materials are specified in the National Sanitation Foundation Standard for Flexible Membrane Liners).

Liner Material Properties

Thickness
1. Overall (mils, minimum)
2. Over scrim (mils, minimum)

Specific Gravity

Minimum Tensile Properties
(each direction)
1. Tensile strength yield
   (lb./inch width)
2. Tensile strength at break
   (lb./inch width)
3. Elongation at yield
   (percent)
4. Elongation at break
   (percent)
5. Modulus of elasticity
   (lb. per sq. inch)
6. Breaking factor
   (lb./inch width)
7. Modulus (force) at 100%
   elongation (lb./inch width)

Water Extraction
(percent loss maximum)

Water Absorption
(percent change, maximum)

Shore A Hardness
(points)

Ozone Resistance

Low Temperature

Dimensional Stability
(each direction, percent change maximum)

Environmental Stress Crack
(minimum hours)

Tear Resistance
(lb. minimum)

Tear Strength
(lb. minimum):
1. Initial
2. After aging

Volatile Loss
(percent loss maximum)

Resistance to soil burial
(percent change maximum in original value):

a.
1. Tensile strength yield
2. Tensile strength at break
3. Elongation at yield
4. Elongation at break
5. Modulus of elasticity
6. Breaking factor
7. Modulus at 100% elongation

b. Membrane fabric breaking strength

Heat Aging
1. Elongation (percent
   minimum)
2. Breaking factor
   (lb., inch, width, min.)

Hydrostatic Resistance
(lb./sq. in. minimum)

Ply Adhesion
(each direction, lb., inch, width, minimum)

Factory Seam Properties

Bonded seam strength*
(factory seam, breaking factor, ppi width)

Peel adhesion

Dead load

Resistance to burial
(percent change maximum in value)
  Bonded seam strength

*Factory bonded seam strength is the responsibility of the fabricator

For example, tests conducted by Haxo (1976) on five different samples of PVC produced the following variations:

Tensile strength (psi)	1540-3400
Elongation (%)	260- 240
Modulus at 100% Elongation (psi)	980-1680
Tear Strength (psi)	270- 390
Water absorption 7 days at 25°C (%)	0.3-1.52

Hypalon products were also tested, and showed similar variations. For instance, water absorption at 100°C after two hours varied from 4.19 - 15.3%.

2.4.1 Misconceptions of Some Common Tests

Some of the data presented by manufacturers may be misleading if the property being tested is not fully understood in the context of liners.

2.4.1.1 Tensile Strength

Tensile strength is the most common test run on liner materials; it is among the easiest of the tests to perform and is probably the least important of the properties associated with flexible liners (Kays, 1977). The tensile strength of a liner increases as its thickness decreases which implies that the best liner would be the thinnest; however, membranes do not fail due to poor tensile strength. When samples fail in a tensile strength test it is more correct to say that failure was due to tearing. The nature of the test is such that the effect of tension causing failure by tearing is masked.

2.4.1.2 Elongation

Elongation at break values are obtained the same time as the tensile strength values. The results show tremendous variation depending on whether the liner is reinforced or unreinforced. The elongation values for reinforced membranes range anywhere from 100 to about 600%. However, the degree of elasticity has little relation to actual liner performance.

At one time liners were installed with excess folds left at the toe of the slopes with the intent that the folds would feed into any depression caused by subsidence of the subgrade. This was contrary to engineering knowledge in that the coefficient of friction between the liner and the relatively rough ground, in addition to the substantial hydraulic head, would limit this borrowing of excess material to an area, infinitely close to the depression.

Elongation is not a usable liner property even during installation. For example, a 10 mil (1 mil = .001 inch) 100 feet square PVC lining cannot be made to cover an area that is 110 feet on a side. This is only a 10% stretch in each direction. (The ultimate stretch of 10 mil PVC lining is 200%.) The amount of force required for a 10% stretch exceeds the limits of practicality.

2.4.1.3 Permeability

The prinicples of liquid movement through a synthetic liner material are different from the hydraulic principles for porous media (Kays, 1977). Liquid passage through a liner occurs through diffusion due to vapour pressure differentials, osmosis due to chemical gradients and absorption due to solubility.

Often suppliers may convert a moisture vapour transmission (perm rating) to "Darcy's" k value, coefficient of permeability, which is meaningless in this situation. It is not useful to compare anticipated liner performances based on this test property (which would explain why this is not a standard test). However, field measurements of permeability of various facilities can be compared. In the field, the measurement includes seepage through pinholes, punctures, tears, poor seams, etc.

3. FLEXIBLE LINER SELECTION CONSIDERATIONS

In selecting a liner and designing a pond the engineer is faced with an assessment of risk versus cost considerations. A complete understanding of the conditions under which the facility will be used and all of the potential failure mechanisms is critical in optimizing the design. An assessment of risk is site and waste specific.

Upon establishing the operating conditions and the level of risk, (regarding waste containment) appropriate liner materials should be selected and considered throughout the design process. The selection of liners requires an understanding of the limitations of available liner materials.

3.1 LINER/WASTE COMPATIBILITY

The chemical composition of the waste to be contained should be known before any flexible liner is considered. Liner selection should also consider the possibilities of concentration build-up through processes such as evaporation, separation, components that tend to accumulate, synergistic effects and shock loadings. Phase separation is also an important consideration since chemical compatibility must be determined for each identified phase.

Any liner that is considered for a project should undergo liner/waste compatibility and seam/waste compatibility verification through a series of laboratory and field tests. The influent and operating temperatures may have a significant impact on the liner due to increased reactivity or sensitivity to the waste material and should be thoroughly investigated.

Oxidizing acids and solvents tend to present the greatest problems to liners. Oxidizing acids attack, to varying degrees, all the linings in common use today, particularly where any combination of high fluid velocity, heat or an impinging stream are encountered. The effects of solvents are more liner specific, but most of them cause problems. The most difficult solvents to contain are aromatic compounds, chlorinated chemicals, turpentine, phenols and ketones.

Wastes containing both aqueous and oily phases may pose special problems because the liner must then resist two fluids that are inherently different in their compatibility with the liner. In fact, various phases may exist between the top and bottom of the contained wastes.

A common misconception is that wastes containing just trace quantities of oil only pose a problem at the oil-liquid interface. This is not entirely true because the oil becomes emulsified and the emulsified product takes on some of the characteristics of the oil itself. The interaction between the oil-water emulsion, or just the oil itself, and other chemicals in the pit can form a sludge that may sink to the bottom.

In terms of seam/waste compatibility heat welded (thermal, extrusion or dielectric) seams appear to have an advantage over other seaming methods due to the homogeneity of the seams.

Tables 3.1 and 3.2 may be a useful guide in the preliminary stages of liner selection. Included in the tables are liner materials other than just flexible liners.

TABLE 3.1 Liner/Industrial Waste Compatibilities (adapted from Stewart, 1978).

	Industrial Waste*						
Liner Material	Petroleum Sludge	Acidic Steel-Pickling Waste	Electroplating Sludge	Toxic Pestiicide Formulations	Oily Refinery Refinery	Toxic Pharmaceutical Waste	Rubber and Plastic
Polyvinyl Chloride (oil resistant)	G	G	F	G	G	G	G
Polyethylene	G	F	F	G	F	G	G
Butyl Rubber	G	G	G	F	P	F	G
Chlorinated Polyethylene	G	F	F	F	P**	F	G
Ethylene Propylene Rubber (PDM)	G	G	G	F	P	F	G
Hypalon	G	G	G	F	P	F	G
Asphalt Concrete	F	F	F	F	P	F	G
Soil Cement	F	P	P	G	G	G	G
Asphalt Membranes	F	F	F	F	P	F	G
Soil Bentonite (Saline Seal)	P	P	P	G	G	G	G
Compacted Clays	P	P	P	G	G	G	G

*P = poor, F = fair, G = good

** Industry claims F or G

TABLE 3.2 Liner Selection Guide Chart (adapted from Kays, 1977).

	Type of Lining									
Substance	PE	Hypalon	PVC	Rubber	Neoprene	Asphalt Panels	Asphalt Concrete	Concrete	Steel	CPE
Water	OK	OK	OK	OK	OK	OK	OK	OK	CP	OK
Animal oils	OK[3]	OK	ST	OK	Q	Q	NR	OK	OK	OK
Petroleum oils (no aromatics)	OK[3]	Q	NR	NR	SW	NR	NR	OK	OK	OK
Domestic sewage	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Salt solutions	OK	OK	OK	OK	OK	OK	Q	NR	NR	OK
Base solutions	OK	OK	OK	OK	OK	OK	OK	Q	OK	OK
Mild acids	OK	OK	OK	OK	OK	OK	OK	NR	NR	OK
Oxidizing acids	NR	NR	NR	NR	Q	NR	NR	NR	NR	NR
Brine	OK	OK	OK	OK	OK	OK	OK	Q	NR	OK
Petroleum oils (aromatics)	Q	NR	NR	NR	NR	NR	NR	OK	OK	NR

1. OK = generally satisfactory, Q = questionable, NR = not recommended, ST = stiffens, SW = swells, CP = cathodic protection suggested.

2. It is recommended that immersion tests be run on any lining being considered for use in an environment where a question exists concerning its longevity. Consult the lining manufacturer or an experienced testing laboratory when in doubt.

3. Must be a one piece lining.

3.2 REINFORCED AND BURIED LINERS

Reinforcement of liners was discussed in Section 2.2.1. In general, reinforced liners have improved dimensional stability, puncture resistance and tear resistance over the corresponding unreinforced liner.

There are disadvantages that should be considered prior to selecting a reinforced liner; these are:

1. low elongation to break;
2. reduced flexibility (decreased ability to conform to subgrade irregularities);
3. greater potential for delamination of membrane plies;
4. possibility of wicking and possible delamination; and
5. higher cost.

Supported liners are typically used in situations where:

1. gas may develop beneath the liner;
2. the water table is high;
3. steep (2.5:1) side slopes are used;
4. there is high wind and wave action;
5. there may be sinkholes; and
6. temperatures are >150°F.

Lining materials whose properties might be adversely affected by heat, ultraviolet radiation, wind, etc. should be buried. An earth cover can be placed over a liner on slopes of up to about 3:1. All flexible liners can benefit from an earth cover, however, precautions must be taken to minimize liner damage during placement of the cover material.

3.3 PROPERTY PROFILES OF SOME COMMON LINERS

Flexible liner manufacturing has changed rapidly over the years; new products are replacing old ones and existing products are constantly being modified or improved upon. It is therefore difficult to present an accurate assessment of all of the commercially available flexible liners. The liners reviewed in this report are based upon common polymers used in the industry and in most cases, the names of the liners are acronyms of the base polymer used in the manufacturing process.

The standard tests and the quality standards for the liners discussed below are presented in Appendix A. Table 3.3 presents a brief summary of the property profiles of the liners discussed below.

3.3.1 Butyl Rubber Liners

Butyl rubber is a polymer of isobutylene (97%) and isoprene (3%). This liner material was among the first to be used for potable water impoundments.

Butyl rubber liners are supplied either supported or unsupported and in thicknesses varying from 20 to 125 mils (1 mm = 39.4 mils) with 45 mils being the most common. These are liners also typically supplied cured or vulcanized (using sulphur). Butyl rubber liners are relatively inexpensive compared to other flexible liners.

Due to the nature of the material ("tight" molecular arrangement), butyl rubber is very resistant to water vapour transmission. It is also considered resistant to ozone attack (unlike natural rubber) and UV (ultraviolet) radiation. Some butyl liners are compounded with EPDM to further improve ozone resistance. Since it is a cured material, butyl rubber does not stiffen at low temperatures and soften at warm temperatures as does PVC and PE. Butyl rubber can be used at temperatures between -45° to 93°C without suffering appreciable degredation in strength and flexibility. The liner also has good tensile and tear strength and good resistance to puncture.

The high density and low permeability of butyl rubber results in seaming problems, as the solvent systems of adhesives cannot readily penetrate the material. Factory seaming is typically done by the using either a rubber solvent prior to curing or a gum tape and adhesives on cured liners.

Field seaming is typically achieved by one of three methods: a one part butyl cement, a two part cement or gummed tape (sometimes used in conjunction with an adhesive). A good seam even under controlled conditions is difficult to achieve, therefore field seaming requires utmost attention. Due to the inherent weakness of butyl rubber seams manufacturers have developed specific seaming methods and procedures.

Butyl rubber liners are not recommended for retention of hydrocarbons and associated solvents and petroleum oils. However, they are highly resistant to mineral acids and to animal and vegetable oils and are only slightly affected by oxygenated solvents and other polar liquids.

3.3.2 EPDM Liners

EPDM, otherwise called Ethylene Propylene Rubber is a polymer of ethylene-propylene dimonomer. EPDM has similar properties to those of butyl rubber. This material is supplied in thicknesses from 20 to 60 mils (45 mils is most common), it is cured (usually by the use of sulphur) and is supplied supported or unsupported. The cost of this liner is generally slightly higher than a comparable butyl rubber liner.

The ozone and UV resistance of EPDM liners are excellent and superior to that of butyl rubber liners. EPDM has excellent resistance to all weathering conditions, and like butyl rubber, can be successfully used over a wide temperature range. For hot water applications, EPDM can be used at temperatures up to 100°C. Marked stiffening of the liner does not occur until temperatures reach the -50° to -57°C range.

Like butyl rubber, EPDM is very difficult to seam due to its tightly knit molecular arrangement. Three seaming methods are typically used: a one-part EPDM cement, a two-part cement, or a gummed tape. In general, the joints are weak. Temperatures during seaming, humidity and cleanliness of the joining layers are critical in obtaining a secure field seam.

EPDM liners are resistant to aqueous acids and alkalis, silicates, phosphates, ketones, alcohols, brine and glycols. This liner material is not recommended for petroleum solvents, aromatic solvents or halogenated solvents.

3.3.3 Neoprene Liners

Neoprene is classed as a synthetic rubber and is based upon the polymer chloroprene. It is supplied in thicknesses ranging from 20 to 60 mils, supported or unsupported and is generally supplied cured. The most common neoprene liners are 21 mils reinforced.

Neoprene is similar to the other rubber liners (butyl and EPDM) in terms of thermal stability, puncture and abrasion resistance, weathering resistance, and resistance to ozone and NV radiation. Neoprene is also similar in the sense that it is difficult to seam.

There are a number of recommended cements to seam neoprene but experience has shown that there is only one that offers a good seam. It is a two-part cement that demands a thorough knowledge of the cement and its application (Owen, 1976). The cement has a very short shelf life, therefore the date of compounding must be known. It also has a very short pot life, therefore the applicator during field application must be able to recognize when the cement loses its proper tack. High temperatures and dry weather conditions are necessary for seaming neoprene liners. The factory fabrication of neoprene is almost identical to that for butyl and EPDM liners, but the resulting joints are stronger because neoprene has better adhesive qualities than most other liner materials. Due to its excellent tack, neoprene is the base material for many industrial adhesive systems.

In terms of chemical resistance, neoprene, unlike butyl and EPDM, has good resistance to wastes containing traces of hydrocarbons. However, its resistance to oils is limited by the resistance of the adhesive seam system to these materials. There have been reports of neoprene liners swelling accompanied by softening and puckering of in oil pit applications after less than one year (Kays, 1977); however the significance of this occurrance was not assessed. It is cautioned that the liner will be affected if aromatics or chlorinated solvents are present in the contained waste.

One of the major drawbacks of neoprene is the cost. On a mil to mil basis it is among the most expensive of the flexible liners.

3.3.4 PVC Liners

PVC, or polyvinyl chloride, liners contain between 30 and 50% of plasticizers and about 2% stabilizers. There are three basic types of PVC liners available: standard PVC, oil resistant PVC, and low-temperature-resistant PVC. Each type is dependent upon the type of plasticizers used in their manufacture.

PVC is one of the most widely used flexible membrane liners for waste impoundments. Factors such as: low cost, good resistance to abrasion, puncture, ozone and biological degradation and good seamability would account for its popularity. Standard PVC is resistant to many inorganic chemicals but suceptible to attack by organic chemicals such as hydrocarbons, solvents and oils. One problem with the standard PVC is migration, over time, of the non-polymeric plasticizers which results in a hard brittle liner. Another disadvantage of standard PVC is that it has a cold crack rating of -10°C to -23°C. Oil-resistant PVC, which uses polymeric plasticizers as opposed to the conventional organic plasticizers, has excellent hydrocarbon resistance but has a cold crack rating of -10°C. Low-temperature-resistant PVC has a cold crack rating of -40°C, however its hydrocarbon resistance is low.

PVC can be seamed by dielectric seaming techniques which are rapid and result in homogeneous bonds. Thermal seaming is another technique which can be used, however this technique is only suitable for thicker membranes. The most popular PVC field seaming method is the solvent adhesive system. When using adhesives it is important to choose one that is compatible with the plasticizers used in the PVC. The plasticizer must not be more soluble in the adhesive resin than in the PVC resin.

Aged PVC liners are often difficult to seam due to irreversible plasticizer and chemical changes and poor low temperature resistance. To repair an aged PVC membrane a strong solvent such as methyl ethyl ketone (MEK) is applied followed by an adhesive.

Due to poor low temperature resistance, and poor weatherability, PVC liners are typically installed with a soil cover.

3.3.5 Polyethylene (PE) Liners

Polyethylene liners are supplied either in the form of low density polyethylene (LDPE) or high density polyethylene (HDPE) which is relatively new on the market. HDPE is compounded free of plasticizers and other filler materials, however it does contain carbon black for protection from UV radiation. HDPE is the most common PE liner used for industrial waste impoundments due to its superior qualities, therefore the following discussion will be restricted to HDPE.

HDPE can be supplied either unsupported or supported and in thicknesses ranging from 60 to 125 mils (which is thicker than most liners used today). Since it is such a thick liner, it is very puncture resistant and less susceptible to mechanical damage and animal abuse. However, due to the thickness, at slightly lower temperatures HDPE becomes difficult to manage.

Through the development of extrusion welding, excellent HDPE seams can be achieved. In addition, HDPE can be manufactured with no seams up to 10 metres wide as compared to typical materials widths of 1.5 metres which are then fabricated to larger sheets (Lewington, 1983).

HDPE exhibits resistance to a wide range of chemicals; whereas LDPE is generally not recommended for oils and aromatics. Sun aging and weathering properties of HDPE are not well documented but are known to be an improvement over LDPE which were recommended to be used as a buried liner.

The material and installation cost of a HDPE liner is higher than most other flexible liners. The fact that LDPE is among the least expensive of the liners available and therefore, depending on the application, may warrant consideration.

3.3.6 CPE Liners

CPE, or chlorinated polyethylene, is produced by a reaction between high density polyethylene and chlorine (25-45%). CPE is generally available in thicknesses of 20, 30 and 45 mil with 30 mil being the most popular thickness. CPE is supplied either supported or unsupported.

Desirable qualities of CPE include; good resistance to UV radiation and ozone, excellent weatherability, resistant to biological degragation, low temperature resistance and good tensile and elongation strength. CPE is resistant to deterioration by many corrosive and toxic chemicals, however at high levels of aromatic hydrocarbons and oils the material tends to swell (U.S. EPA, 1980) but regains most of its original properties after drying. Continuous exposure to high levels of aromatic hydrocarbons will shorten the life of the liner. CPE dissolves in chlorinated hydrocarbon solutions. If one is considering using CPE under high temperatures (above 70°C) a careful assessment of this material under these conditions should be done.

CPE's inertness to many compounds makes seaming difficult. Typical methods of seaming CPE are by using bodied-solvent adhesives, solvent welding or by dielectric heat sealing.

CPE is often compounded with other polymers such as PVC, PE and a number of rubbers in order to improve the resistance of some of these other materials. PVC addition to CPE can improve the seamability of CPE and may contribute to improve the overall stability and hydrocarbon resistance of the final product.

3.3.7 Hypalon (CSPE) Liners

Hypalon, or chlorosulphonated polyethylene (CSPE), is manufactured by reacting a solution of polyethylene with chlorine (25-45%) and sulphur dioxide (1-1.4% sulphur). Hypalon is classified between a rubber and a plastic. When it leaves the manufacturer it more closely resembles a plastic but with time it slowly cures into an elastomeric type material.

Hypalon is most often supplied supported in order to minimize shrinkage. The most popular thicknesses are 30, 36 and 45 mils.

Hypalon is characterized by good resistance to: ozone, UV radiation, low temperature cracking, biological attack and deterioration by corrosive materials such as acids and alkali, and good weatherability. Hypalon also has the highest specific gravity (1.5) of all the flexible liners which makes it very suitable for use in situations which can cause low density unburied liners to float (eg. brine ponds). Disadvantages of hypalon liners are: low tensile strength, tendency to shrink when exposed to sunlight (these properties can be improved through reinforcement) and poor resistance to oils (although better than butyl liners) and aromatic hydrocarbons. As the material cures tensile strength increases, elogation strength decreases and hydrocarbon resistance will improve.

Cured hypalon is more difficult to install and seam than the uncured material, therefore, precautions should be taken to slow the curing process when storing (ie., protect from sunlight). Hypalon can be easily seamed in its uncured state by means of thermal sealing, dielectric heat sealing, solvent welding or by using a bodied solvent adhesive (an adhesive made up of hypalon blended into a solvent). As the material cures, dielectric heat sealing or thermal sealing are the recommended seaming methods. Field seaming is generally done using the bodied solvent adhesive which, for this material, produces and excellent seam.

TABLE 3.3 Summary of the property profiles of some common flexible liners.

LINER	ADVANTAGES	DISADVANTAGES
1. BUTYL RUBBER	1. highly impermeable to water vapour 2. thermal stability - 45° to +93°C 3. good ozone and weathering resistance 4. resistant to animal/veg., oils oxygenated solvents, polar liquids 5. good puncture resistance 6. low cost	1. poor seamability 2. poor resistance to many hydrocarbons (petroleum related)
2. EPDM	1. highly impermeable to water vapour 2. thermal stability, good heat resistance (temperature range of about -50° to 100°C) 3. excellent ozone and weathering resistance 4. resistant to aqueous acids and alkali, silicates, phosphates, ketones, alchols, salt water and glycols 5. cost is comparable to butyl rubber	1. poor seamability 2. poor resistance to petroleum solvents, aromatic and halogenated solvents
3. NEOPRENE	1. similar to butyl and EPDM 2. good performance in dilute oils without aromatics (petroleum related) 3. thermal stability similar to butyl rubber	1. poor seamability 2. strongly attacked by chlorinated solvents 3. among the most expensive
4. PVC	1. low cost 2. good resistance to abrasion 3. good resistance to ozone 4. excellent seamability 5. resistant to a wide range of chemicals	1. poor weatherability 2. poor low temperature resistance, cold crack rating of -10°C (with the exception of low temperature resistant PVC, cold crack rating of -40°C)

TABLE 3.3 (continued)

LINER	ADVANTAGES	DISADVANTAGES
5. HDPE	1. excellent resistance to puncture, mechanical abrasion and animal abuse 2. wide range of chemical resistance including oils with aromatics 3. excellent seams can be achieved	1. high cost 2. very stiff, therefore may cause installation difficulties 3. relatively new on the market, therefore limited performance information
6. CPE	1. good resistance to UV radiation, ozone and weathering 2. resistant to biological degradation 3. low temperature resistance 4. good tensile and elongation strength 5. wide range of resistance to corrosive and toxic materials 6. can be compounded with other polymers	1. difficult to seam 2. continuous exposure to high levels of aromatic hydrocarbons is not recommended 3. high temperature operation is questionable
7. HYPALON (CSPE)	1. good weatherability, ozone and UV resistance 2. resistant to low temperature cracking, biological attack and resistant to corrosive acids and alkali 3. high specific gravity	1. unreinforced liners have low tensile strength and high shrinkage (when exposed to sunlight) 2. poor resistance to oils (better than butyl rubber) and aromatic hydrocarbons

3.4 FAILURE MECHANISMS

An awareness and understanding of all possible pond failure mechanisms is essential in order to plan and design impoundment facilities. Kays (1977) has established a list of principle failure mechanisms appropriate for all types of liners and categorized them as shown in Table 3.4. For the purpose of this report the failure mechanisms will be examined under the context of flexible liners although they may also be applicable to other liners. The failure mechanisms have been divided into the categories of physical, chemical and biological as shown in Table 3.5.

Liner failures generally stem from problems in the subgrade, the liner itself, weathering, operating procedures and/or liner/waste chemical incompatibility.

3.4.1 Physical Failures

Physical failures of liners are often subgrade related; for example, problems associated with compaction, differential settling, slope sluffing, texture and build-up of gas and hydrostatic pressure. The physical characteristics of the liner material itself may be the only cause of liner failure or it may be directly associated with subgrade problems. Other aspects to be considered under physical failures are operating problems (eg., cavitation, impingement and maintenance), vandalism and damage by animals. The modes of liner failure which can be attributed to one or more of the above physical processes are discussed below.

Puncture failure is very common in flexible liners and can be attributed to subgrade texture, pond operations, ice, man or vehicles, burrowing animals or animals seeking water. A smooth subgrade, good pond operating procedures and possibly burying the liner could minimize puncture failure. Tear failure results

TABLE 3.4 Classification of the principle failure mechanisms for cut-and-fill reservoirs (Kays, 1977).

Supporting structure problems

- The underdrains
- The substrate
    - Compaction
    - Texture
    - Voids
    - Subsidence
    - Holes and cracks
    - Groundwater
    - Expansive clays
    - Gasing
    - Sluffing
    - Slope anchor stability
    - Mud
    - Frozen ground and ice
    - The appurtenances

Lining problems

- Mechanical difficulties
    - Field seams
    - Fish mouths
    - Structure seals
    - Bridging
    - Porosity
    - Holes
    - Pinholes
    - Tear strength
    - Tensile strength
    - Extrusion and extension
    - Rodents, other animals and birds
    - Insects
    - Weed growths
- Weather
    - Rain, UV radiation, solar radiation
    - Wind
    - Ozone
    - Wave erosion
- Seismic activity

Operating problems

- Cavitation
- Impingement
- Maintenance (cleaning)
- Reverse hydrostatic uplift
- Vanadlism

TABLE 3.5 Failure categories for flexible liners.

Physical	Chemical and Biological
Puncture	Ultraviolet light
Tear	Ozone attack
Extrusion	
Creep	Hydrolysis
Differential settling	Ionic species attack
Temperature differentials	
Negative hydrostatic pressure	Extraction
Gas pressure	
Field seam problems	Solvents
Pinholes	
Weed growth	
Wind and wave action	
Cavitation and impingement	
Maintenance	
Vandalism	
Animals	

from several stress-relaxation cycles and is similar to puncture failure in its occurrence. Tear failure is best minimized by using a reinforced liner and by minimizing any tension stress areas. Somewhat similar to puncture, is extrusion which is a manifestation of elongation. A hole or crack can result in the liner extruding into it and rapidly exceeding the maximum elongation. A flexible liner on crushed rock may resist puncture, however extrusion could be a deciding factor for failure.

Differential settling results in localized structural stress. Through careful geotechnical investigations and subgrade design as these stresses can be minimized. Liner creep, which is defined as increased liner deformation under a sustained load, is unlike differential settling in that it is difficult to detect and control.

Temperature extremes can promote physical failures through either an increase in brittleness when cold or a more rapid reaction (expansion) to stresses when hot. However, if the liner is not subjected to impact loadings in freezing weather there is little concern since the flexible membranes will again become pliable. Other physical failure mechanisms due to weathering include wave action and wind uplift effects.

The effect of reverse hydrostatic pressure on pond integrity is probably the second most serious problem next to subgrade problems. Hydrostatic pressure due to a high groundwater table can result in liner uplift, stretch and/or structural weakness (Kays, 1977) caused by the pumping action of water moving in and out between the liner and subgrade when impoundment levels fluctuate. The problem can be alleviated by proper design of underdrainage systems. Similar to reverse hydrostatic pressure, gas can collect beneath the liner (ie., natural gas or air) and result in massive liner uplifts when the gas pressure exceeds the hydrostatic head in the pond. Methods to prevent this problem include a gas venting system or ballasting the liner with an appropriate amount of soil cover (30 to 50 cm).

The application of a protective, soil cover over the liner can contribute to liner failure. Careful consideration must be given to the cover material used and the method of application in order to prevent liner puncture, tearing and/or stretching.

Many liner failures can be attributed to either the lining itself or field fabrication. Field seams can fail due to a number of causes which include: poor adhesive, dirty bond surfaces, excess moisture, improper temperature during bonding and poor liner layout. One common seam problem termed "fish mouth" generally occurs in cured rubber liner seams where the adhesive is slow to develop full strength. If the membrane is stretched prior to the seam achieving full strength and one piece stretches more than the mating piece, one area of the joint may pop open creating a "fish mouth". The liner material itself may have holes which may have developed during manufacturing or handling (mainly during installation). Pinholes occur mainly in the manufacturing process due to foreign particles, burnt resin in the mix, etc. and these can be focal points for tearing. Pinholes are more prevalent in the thin single ply liners and as the liner thickness and number of laminations increase pinhole problems decrease.

Weed growths can cause considerable damage to liners. Weeds can penetrate up through a liner or the roots can penetrate down into buried liners. It is therefore important in subgrade preparation to apply a weed killer to the soil should weeds be a suspect problem. Good maintenance can minimize weed growth above buried liner ponds.

Certain pond operations can result in liner failure if proper control measures are not taken. Cavitation (bubble implosion resulting in high pressure intensities) at pumps, at inlet or outlet structures, and at flumes can result in liner fatigue (through pitting). To prevent this problem requires proper hydraulic design. Impingement (incoming solution hitting the liner) is another operations problem, that results in liner vibration and substrate displacement. The installation of energy dissipators would be the solution to this problem. Maintenance of a facility is an obvious problem and detailed precautions should be outlined to the staff in order to protect the liner.

3.4.2 Chemical and Biological Failures

Liner/waste compatibility is extremely important. Swelling is a common liner/waste reaction and can result in a loss in strength. A liner with a high degree of crosslinking (such as CSPE or CPE) or one with a high level of crystallinity (such as HDPE) reduces the ability of a polymer to swell and to dissolve. Extraction of a plasticizer is common with liners containing large amounts of monomeric plasticizer (such as PVC); this results in embrittlement and shrinkage.

Ozone and UV attack are two other common chemical related liner failure mechanisms. These problems can be mitigated by burying the liner. Failures due to such exposure to light and air generally result in embrittlement, shrinkage and breakage. Some flexible liners have been developed which are relatively resistant to ozone and UV radiation.

As discussed in Section 3.1, a liner and its seams should undergo chemical compatibility tests with the waste it is expected to contain.

Biological failure of a liner is failure induced by soil or waste microbial attack. Some of the plasticizers used in liner manufacturing are particularly susceptible to such attack. Bactericides are sometimes used to prevent this type of failure.

4. POND DESIGN, CONSTRUCTION AND OPERATION CONSIDERATIONS

Several considerations must be taken into account when planning and designing a waste impoundment. First and foremost is site selection which plays a significant role in determining the ultimate cost of the facility. Pond liner requirements have to be assessed in relation to all site limitations, possible failure mechanisms, required service life, leakage tolerance level and monitoring requirements.

Liner selection should be considered throughout the design steps, but should not be considered the "key" to a successful impoundment. The liner is as important as all other aspects of pond design since all elements must successfully perform their task for the pond to be effective. The most important point to recognize throughout the design is that the flexible liner must be placed in a stable structure; the liner itself is not stable in its own right.

4.1 SITE SELECTION AND ASSESSMENT

There are several factors which should be considered in the selection of the pond site. In many instances the general location of a pond may be predetermined, in which case it is important to do a careful site assessment and analysis since the pond design will depend on the environment constraints within which it is being constructed. Table 4.1 is a list of factors which should be evaluated for any proposed site.

Native soils are a primary factor in any pond design. They should be tested to determine factors such as Atterberg limits and grain size relative to "shrink/swell" moisture, density, strength, settlement, permeability, organic content, mineralogy, ion exchange capacity and solubility (U.S. EPA, 1980).

TABLE 4.1 Factors to be evaluated for site selection, assessment and design.

Geological	- stratigraphy
	- characteristics of soil materials
	- location of bedrock
	- fault zones, fractures
	- stability of materials, estimate of settlement
	- availability of construction material
	- chemical activity of soil
	- potential for gas generation
Hydrological	- identification of aquifers
	- groundwater table
	- groundwater recharge/discharge areas
	- groundwater flow
	- groundwater and surface water quality
	- surface drainage patterns
	- evaluation of streams, rivers, lakes and/or ponds (normal, high, 100 year storm levels)
Meteorological	- temperature extremes and durations
	- annual precipitation
	- wind data (velocity and direction)
	- frost depth
Environmental	- characteristics of waste to be impounded
	- area's reliance on groundwater or surface water
	- proximity, quality and depth of nearby wells
	- proximity of residences
	- future proposed land use
	- vegetation

Soils with high "shrink/swell" characteristics should be avoided. Soils with high organic content may result in gas pressure on the liner and/or the development of voids; therefore these soils require special attention. Similarly, any soluble portion of the soil may result in the same occurrences and therefore require close investigation.

4.2 SUBGRADE PREPARATION

Subgrade performance is a function of loading, groundwater levels, slope stability and liner integrity.

The most economical shape for an impoundment is rectangular since it minimizes grading and liner installation costs. The basic impoundment design most often used is the "cut-and-fill" type (partially excavated bottom with raised berms).

The excavated pond area should be proof-rolled and any soft areas should be removed and replaced with a suitable compacted soil. The subgrade soil on which the liner is to be placed should be bladed smooth. The subgrade soil should not contain particles greater than 13 mm (1/2 in.) and angular particles should not be present. Fill should be placed in lifts specified by the geotechnical engineer. Each lift should be compacted. Compaction requirements are generally specified as percentage relative compaction based on the "Modified Proctor" and achieved on the dry side of optimum moisture content. A desirable degree of compaction would be about 95% of the maximum dry density (Modified Proctor).

The finished subgrade surface should be firm, smooth and free of any sharp objects. Typically, a finished subgrade consists of poorly graded sand (ie., uniform particle size, 50% of which is smaller than #4 seive) of 10 to 15 cm thick, smoothed and compacted. Geotextile fabrics placed over the substrate may provide a cushion for the liner in order to protect it from abrasive action and reduce the coefficient of friction between the liner and substrate and establish a permeable layer for gas and vapour transmission. The effectiveness of geotextiles for these uses is unproven, however their use for these purposes are becoming more common.

The floor of the impoundment should be sloped if there is a possibility of gas pressure building beneath the liner (through organic decay or water table fluctuation). A slope of no less than 2.5% from the center to the toe of the dyke is recommended. The venting medium, either geotextile or sand, is contained over the entire bottom and side slopes. Venting to the atmosphere is achieved by gas vents placed on the inside slope of the berm about 30 cm below the crown of the berm. These gas vents are generally placed 7 to 15 m apart. (Figure 4.1).

An underdrain system is established where it is necessary to monitor/control leakage through the liner and/or relieve negative hydrostatic pressure. The system includes a main collection header with lateral interception drain and a collection sump or sewer. The perforated interception pipes (typically 4" PVC) are placed in gravel and geotextile lined trenches. They intercept water (or wastewater) flowing laterally in the pervious geotextile or sand layer above. (Figures 4.2 and 4.3).

The side slopes of impoundments are typically 3:1 and no less than 3:1 for ponds using a buried liner system. It is recommended that the side slopes be sprayed with a herbicide if weeds may be a problem.

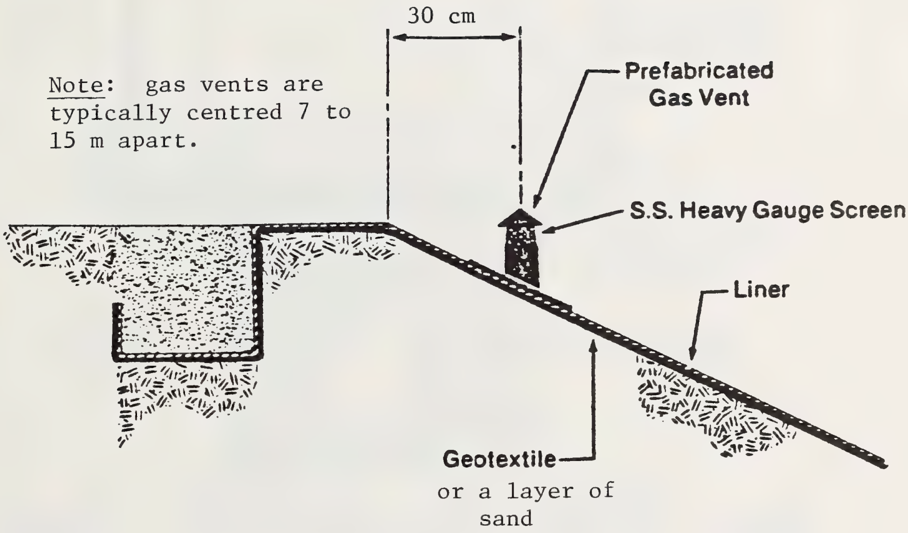


Figure 4.1 Gas Vents (adapted from Kirby, 1979).

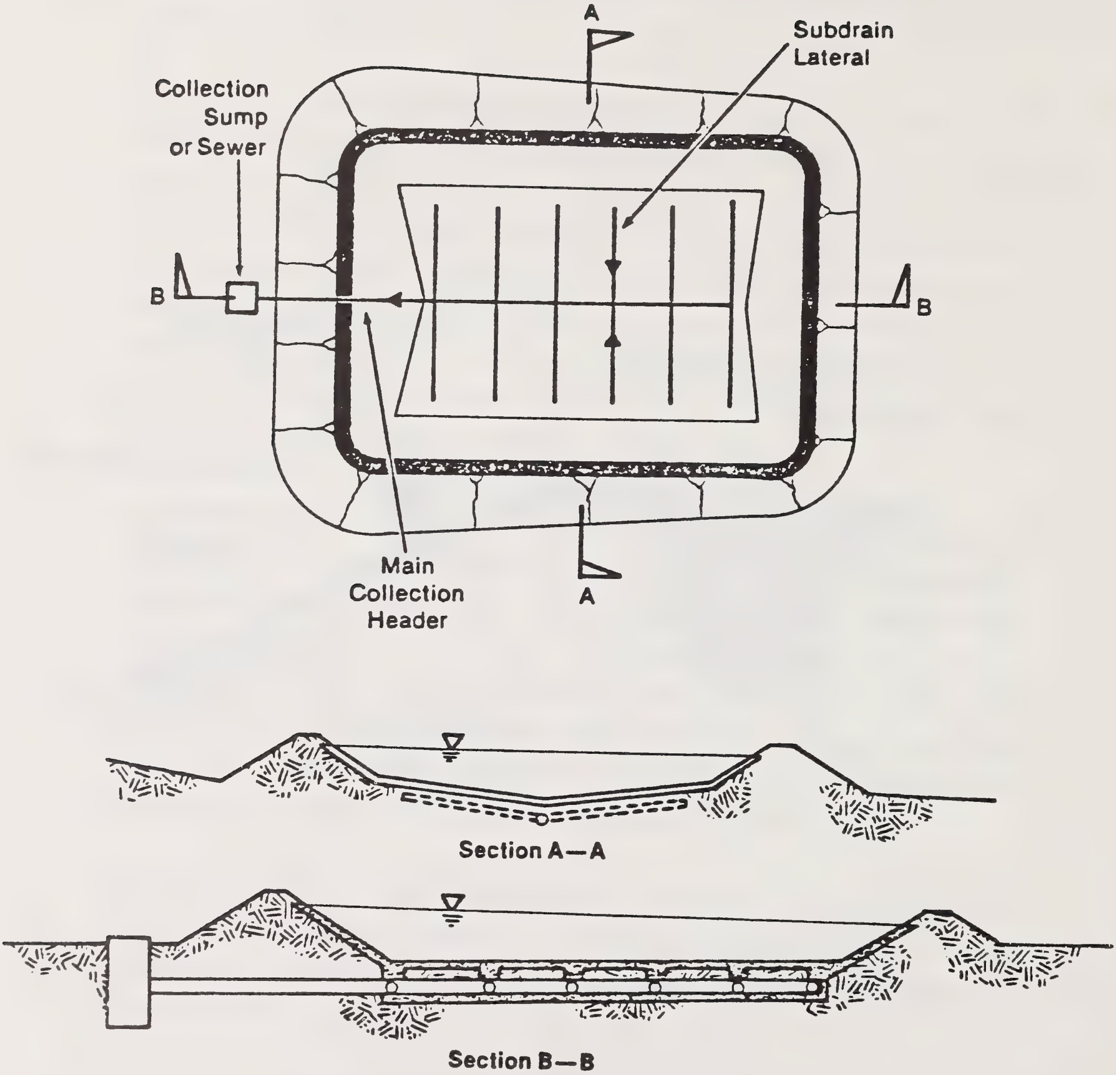


Figure 4.2 Underdrain System (Kirby, 1979).

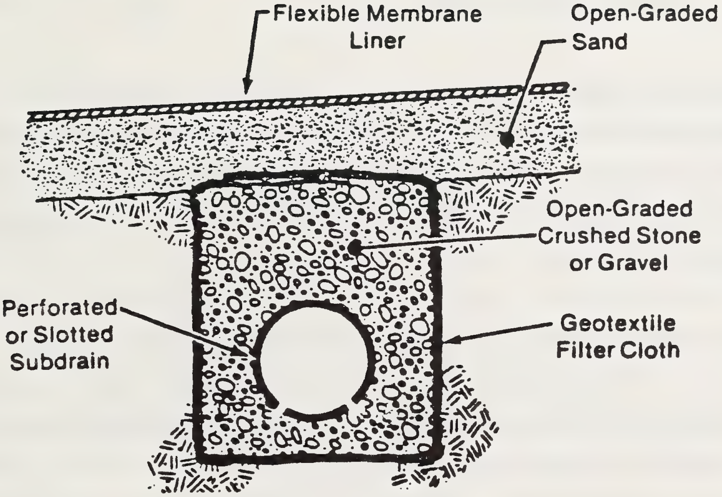

Flexible Membrane Liner
Open-Graded Sand
Open-Graded Crushed Stone or Gravel
Perforated or Slotted Subdrain
Geotextile Filter Cloth

Figure 4.3 Subdrain Lateral Crossing Section (Kirby, 1979).

Structures such as inflow, outflow, and overflow pipes should be designed, if possible, such that they do not penetrate the liner. If this cannot be achieved then the materials selected for these structures should compatible with the liner material. Appropriate design measures should be taken to prevent problems of cavitation and impingement.

The top width of the dyke should be at least 2.4 metres to allow access by maintenance vehicles. The dykes should be designed to prevent surface runoff entering the impoundment.

4.3 LINER INSTALLATION

Following the selection of an appropriate liner careful consideration must be given to installation. Factors to consider when planning the installation of the liner are storage, equipment, manpower, placement, field seaming, quality control and inspection.

Flexible liners are generally shipped in rolls or in folded panels. This material should be covered in order to protect it from weathering (particularly from sunlight) and fenced or housed if vandalism is a concern.

The manpower requirements for installation are quite high and generally a function of the required rate and complexity of installation, as well as the experience of the crew. Typically 5-10 people are required to place one panel. The installation crew should be supervised by an individual with experience in installing the type of liner selected.

Prior to moving panels into place an anchor trench should be excavated around the perimeter of the impoundment. The anchor trench should be about 30-50 cm wide, about 30 cm deep and should be set back about 30-50 cm from the top of the slope. Other aspects to consider prior to placement of the liner are: ensure that the subgrade is smooth, ensure that there is no standing water in the facility and ensure that all structures, skirts and other appurtenances are in place and prepared.

The liner is generally rolled or unfolded down the side slope or across the bottom. It is then spotted into position with overlap of between 10 to 30 cm depending on the manufacturer's specifications. Sufficient slack should be left in the material to accommodate any possible shrinkage due to temperature changes Once the liner is spotted it is generally held in place with sandbags or tires.

One of the most important aspects of liner installation is seaming. The factors to consider in field seaming are: ambient temperature, humidity, substrate moisture, consistency of the adhesive, cleanliness of the bonding surfaces and airborne particles. There are a number of methods used for seaming the various liners (as discussed in section 2.3.1) and the method used should be the one recommended by the manufacturer.

During seaming, a long board is often placed beneath the bonding surfaces in order to provide a smooth flat support. The board is moved along as the surfaces are bonded. Wrinkles should not be present in the seam. If an adhesive is being used it should be applied uniformly. Normally seaming begins in the middle of the panel and work proceeds towards each end to minimize the occurrence of large wrinkles. Seams oriented perpendicular to the toe of the slope minimize stress on the seams. Sufficient dwell time should be allowed to ensure that full bond strength has been achieved.

Seaming under adverse conditions (ie., very cold, very hot, damp, etc.) requires that special considerations be given to adhesive systems and temperature limitations.

Material properties, particularly of thermoplastics, change with temperature. The rate of solvent evaporation and therefore the dwell time are also affected by temperature. Heat guns can be used to bring the liner temperature within a working range, however caution must be exercised around flammable solvents which may generate toxic gases when ignited. Generally the number of panels placed in one day should not exceed the number that can be seamed the same day.

Proper tailoring and sealing of a liner around any penetrating structures is essential. Several methods are available to obtain a good seal. First, the selection of the material to be used for the structure should be compatible to the liner selected and appropriate preparations (such as anchor bolts) made. A common practice is the use of boots that slip over pipes. The back of the boot is bonded to the main liner and the front of the boot is banded (stainless steel) to the end of the pipe.

Special precautions must be given where impingement may be a problem, (eg., at the inlet structure). The use of splash pads troughs can be constructed to alleviate this problem. Additional layers of liner at the point of impact, the use of geotextile beneath the liner or a concrete pad beneath the liner can be used depending on the anticipated severity of the problem. Two typical designs are shown in Figures 4.4 and 4.5.

After the liner is in place it is important to examine the liner for any possible faults, paying particular attention to the seams and seals around appurtenances. An air lance is a useful method of testing field seams. The air lance is typically operated at 345 kPa (50 psi) pressure and discharging air through a 4.8 mm (3/16 inch) orifice and held at about 15 cm from the seam. It is also important to ensure that all scrim (if a reinforced liner is used) is encapsulated in order to prevent wicking.

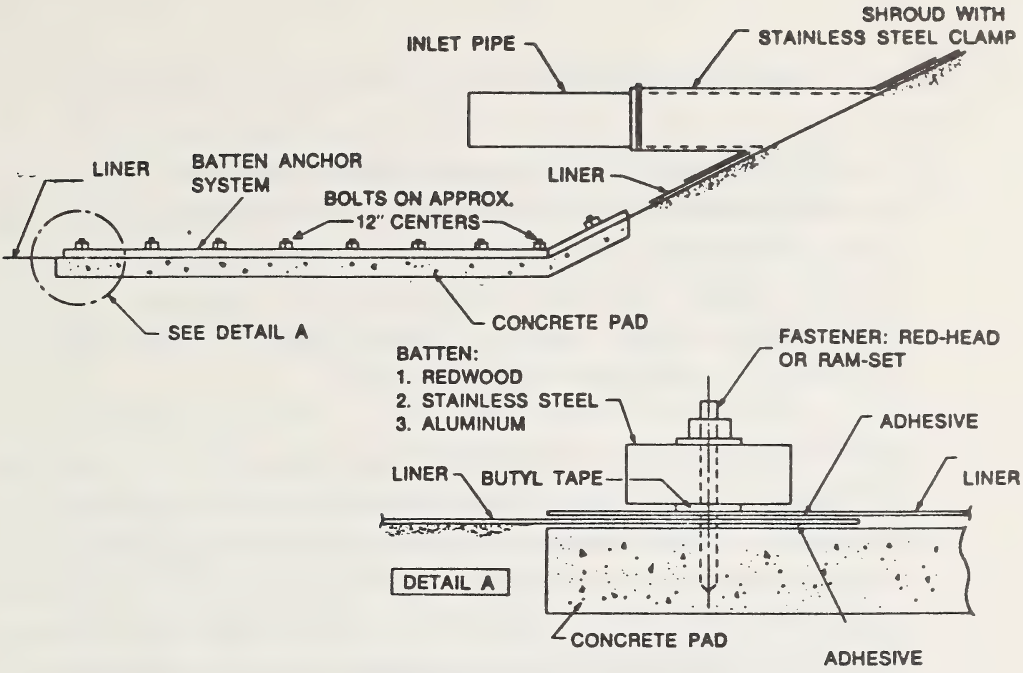


Figure 4.4 Splash pad using a concrete subbase (U.S. EPA, 1980).

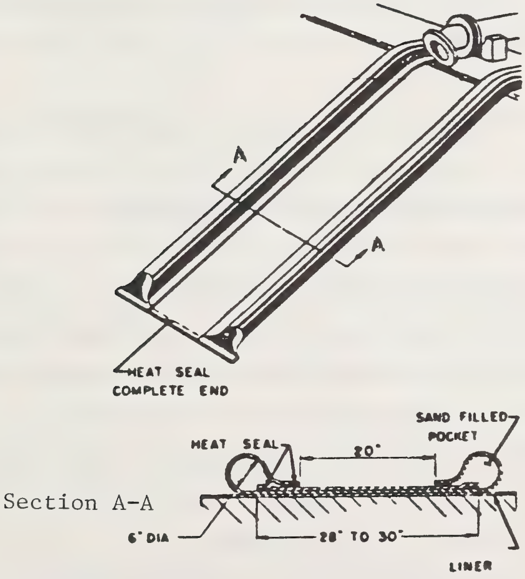


Figure 4.5 Sluice type trough constructed of liner material (U.S. EPA, 1980).

4.4 PROTECTIVE SOIL COVER

A protective layer of soil is often placed over a flexible liner in order to protect it from weathering (particularly freeze thaw cycle, ice damage, UV radiation and ozone), mechanical damage, animals, vandals and also to prevent liner floation. A soil layer can also reduce potential adverse impacts of chemicals on the liner by minimizing the contact area.

It has been found that the maximum slope ratio of 3:1 is required to maintain a soil cover. The soil cover should be applied in a minimum of a 45 cm lift (well graded sand is recommended) with a moisture content on the dry side of optimum to minimize compaction effort (U.S. EPA, 1980). The material should be free of angular objects and should be stable and resist sloughing as a result of wave action. The material should first be "end dumped" over the liner and leveled with the use of a crawler track mounted bulldozer. Equipment should never be allowed directly on the liner material and any sharp turns while over the liner should be avoided.

Some of the disadvantages of soil covers include: an increased chance of liner puncture during cover placement and increased difficulty in locating and repairing leaks.

In larger impoundments it may be necessary to place a soil cover to protect side slopes from wave action. Wave action can result in sloughing of dry cohesionless subgrade soils. Wave impact can also increase the pore pressure of subgrade soils having high moisture content. As the wave recedes this results in a low pressure above the liner causing a pulling force on the liner and soil and may result in slope failure.

Typical side slope protection would consist of a 45 cm lift of well graded sand on the liner, a 30 cm lift of well graded gravel, and then a 45 cm lift of rip rap. Geotextile may or may not be required between each layer of soil depending on quality of the soil covers.

4.5 COUPON TESTING

An important aspect of any impoundment lined with a flexible liner is being able to assess/monitor the condition of the liner with time. The method employed to assess the liner condition is called a coupon test. This test involves placing one or more 30 cm^2 (minimum size) pieces of liner in the impoundment such that they are subject to the same environmental conditions as the liner itself. The coupons must be placed where they can be easily retrieved. This factor should be considered in the design stage of the impoundment. The coupon can provide valuable information on the physical and chemical integrity of the liner which can be used to determine the useful life of the liner. Liner replacement can then be planned accordingly.

4.6 LEAKAGE TOLERANCE

Due to material limitations, a liquid waste impoundment of the cut-and-fill type lined with a flexible liner cannot be designed 100% leak proof. The allowable amount of leakage must therefore be defined. A formula developed by the East Bay Water Company of Oakland, California, defines leakage tolerance as (Kays, 1977):

$$Q = \frac{A \sqrt{H}}{80} \quad \ldots\ldots\ldots\ldots (1)$$

where: Q = maximum permissible leakage tolerance (gpm), not less than one gallon per minute;

A = lining area (1000's of square feet);

H = maximum head (feet).

For example a rectangular impoundment with:

top dimensions, 200 feet x 300 feet (61 m x 91 m);
side slope, 3:1;
total depth, 20 feet (6.1 m);
freeboard, 4 feet (1.2 m);
therefore, maximum head (H) is 16 feet (4.9 m);
(pond capacity at 16 feet is 3.577 million U.S. gallons (1.35×10^4 m^3));
wetted liner area (A), 62.068×10^3 square feet (5.77×10^3 m^2);

would have a leakage tolerance (Q) of 3.1 U.S. gpm or 16.9 m^3/d.

Using Darcy's law (Holtz, 1981) (although seepage through flexible liners is not controlled by the same hydraulic principles as through a porous media as discussed in 2.4.1.3 of this report, this expression is being used to discuss seepage in terms of "apparent" hydraulic flow):

$v = ki$ where . . . . (2)

$i = \frac{\Delta h}{L}$ and

$Q = kiA$

where:

Q = flow through cross-sectional area A, 16.9 m^3/d;

A = area, 5.77×10^3 m^2;

k = coefficient of permeability;

i = hydraulic gradient;

Δh = head loss, 4.9 m (assuming that the pressure head below the liner is atmospheric);

L = liner thickness, 40 mil or 1.02 mm ; and

v = velocity or Darcy flux (rate of seepage from the impoundment).

the "apparent" rate of seepage from the above impoundment is:

$$v = \frac{Q}{A} = \frac{16.9\ m^3/d}{5.77 \times 10^3\ m^2} = 2.93 \times 10^{-3}\ \frac{m}{d} \text{ or } 3.39 \times 10^{-6}\ \frac{cm}{s}$$

and the "apparent" permeability of the liner is:

$$k = \frac{v}{i} = v \times \frac{L}{\Delta h} = 3.39 \times 10^{-6}\ \frac{cm}{s} \times \frac{.001\ m}{4.9\ m} = 6.9 \times 10^{-10}\ \frac{cm}{s}$$

Equation 1 is simplified in that it assumes a constant head over each section of the liner which is not the case, it also does not account for leaks at the various appurtenances. In some applications of equation 1 the denominator has been doubled to 160 which reduces the tolerance by 50%. Equation 1 and any modifications of the equation should be used only as a guide. A careful assessmment of the site and contained waste in terms of the environmental implications of seepage should be the governing factor in establishing a leakage tolerance level. All impoundments lined with flexible liners should be capable of acheiving a coefficient of permeability of at least 10^{-7} cm/s and the best that can be expected of a site is probably 10^{-10} cm/s. To achieve a coefficient of permeability of less than 10^{-10} cm/s, the costs become unreasonable and other alternatives should be investigated.

Groundwater quality standards or criteria are generally based on existing or potential use of a groundwater supply. The most stringent criteria are based on a drinking water use. A summary of the Guidelines for Canadian Drinking Water Quality 1978 is presented in Appendix B.

4.7 MONITORING

Measuring the performance of a liner can be conducted by monitoring the drainage system below the liner and/or monitoring the groundwater.

The drainage system collects groundwater and/or seepage from the impoundment and discharges it to a sewer or sump. At the sewer or sump the water is monitored in terms of quantity and quality. If seepage is detected and presents a potential pollution problem, the wastewater should be pumped back into the pond. Should the observed rate of seepage increase to unacceptable levels the pond should be drained and carefully examined to determine the source and cause of the problem.

Groundwater monitoring is a very complex task. It is necessary to identify the hydrogeological regime which includes water table level and groundwater flow and depth. It is also necessary to identify the geology, geochemistry and water chemistry in the area. This information is then used to predict the direction and rate of flow of pollutants seeping from an impoundment as well as any pollutant attenuation that might occur. The selection of monitoring sites require careful hydrologic judgement.

Once a prediction of pollutant migration is made a method of monitoring this migration must be established. Monitoring should be conducted in either the vadose zone (unsaturated zone) or in the zone of saturation depending upon the rate of movement. Figure 4.6 shows a simplistic view of the percolation of pollutants from a liquid waste impoundment. Any layering of strata may cause considerable lateral movement of the seepage.

In the vadose zone, attenuation, travel time and storage capacity may be very high. In this zone chemical changes such as

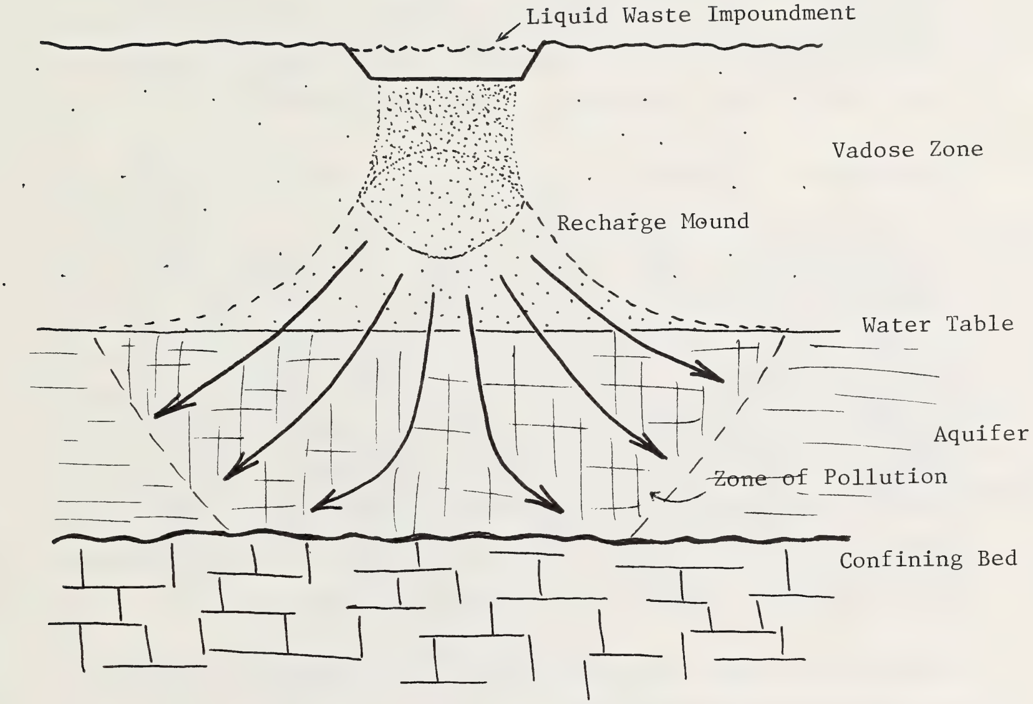


Figure 4.6 Perculation of pollutants from a liquid waste impoundment (Todd, 1976).

precipitation, dissolution, ion exchange, adsorption and oxidation and reduction may be significant. Monitoring in the vadose zone is generally conducted directly beneath the structure.

Water flow is measured by using piezometers (in saturated conditions) or tensiometers (in unsaturated conditions). In saturated zones water samples are obtained by using a simple bailer in a well, a dysimeter or sampling chambers and in unsaturated zones by soil sampling or suction cups. The zone of saturation is the zone which is most often monitored.

The pattern of groundwater movement has a major effect on the distribution of groundwater pollutants. Geochemical considerations are also a prime concern. In order to monitor the saturated zone wells are required which are either dug, augered, driven, jetted or drilled. There are a number of different casing materials available such as PVC, rubber modified polystyrene, epoxy plastic, steel or black pipe. The casing is slotted at the depth of the water bearing strata and the slot size is proportional to the particle size of the strata. Well screens are often used to optimize the open area percentage. Water samples are obtained by pumping or by bailing.

Sampling is typically carried out on a monthly, seasonal or annual basis depending on the rate of groundwater movement. Typical groundwater flow velocities fall in the range of 5 feet per year to 5 feet per day (Todd, 1976). The major parameters used to monitor water quality can be classified as either physical, organic, inorganic, bacteriological or radiological. Significant removal of organic, bacteriological and radiological constituents of percolated wastes can occur in the topsoil and vadose zone. Parameters which fall in the organic and inorganic classes tend to be the easiest to monitor. It is generally recommended that the major cations (Ca^{++}, Mg^{++}, Na^{+} and K^{+}), major anions (CO_3^{-2}, HCO_3^-, Cl^-, SO_4^{-2} and NO_3^-), pH, conductivity, and total dissolved solids be determined. Additional consideration is then given to parameters related to the specific use of the groundwater and to the wastewater. The organic compounds and inorganic compounds that are generally of interest are shown in Table 4.2 and Table 4.3, respectively. Once the groundwater and percolated wastes have been qualitatively monitored a few key parameters may be used as seepage indicators. It should be noted that waste constituents generally have varying rates of mobility under varying conditions.

4.8 MANAGEMENT

Proper management is necessary to ensure the proper performance of an impoundment and to otimize the life of the facility. It is the responsibility of the operating crew to protect the integrity of the liner, monitor the performance of the facility and monitor the condition of the liner. An operations and procedures manual should be established for the facility and should be drafted by the design, construction and operations crew. The following major aspects should be included in the manual:

- "as-built" drawings
- materials of construction
- hydrogeological data
- geochemical and groundwater quality data
- acceptable and unacceptable wastes
- sludge handling
- trouble shooting
- maintenance
- monitoring the facility and the liner
- operation variables and procedures
- unacceptable practices
- safety precautions when working around a lined impoundment

It is important that the operator is fully aware of all the liner characteristics and properties since once the facility is built the liner is the focal point of the system.

TABLE 4.2 Primary organic constituents with respect to polluted groundwater (Everett, 1976).

- Carbon
- Biological Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Methylene Blue Active Substances
- Nitrogen
- Phenolics
- Insecticides and Herbicides

TABLE 4.3 Primary inorganic constituents with respect to polluted groundwater (Everett, 1976).

Major	Ca^{++}, Mg^{++}, Na^{+}, K^{+} CO^{-2} HCO_3^{-}, SO_4^{-2}, Cl^{-} NO_2^{-} Total Dissolved Solids pH Conductivity
Other	Si^{+4}, B^{+++}, F^{-} Nitrogen forms Phosphorus forms Hardness
Drinking Water Trace	Fe^{++}, Mg^{++}, $As^{+3,+5}$, Ba^{++}, Cd^{++}, Cr^{+6}, Cu, CN^{-}, Pb, Se, Ag^{+}, Zn^{++}
Other Trace	V, Mo^{+6}, Br^{-}, I^{-}, Al^{+3}, Co, Li^{+}, S, Be^{++}
Gases	Methane Hydrogen Sulphide Carbon Dioxide Dissolved Oxygen Residual Chlorine

5. CONCLUSIONS

The flexible liner industry is a rapidly changing field in terms of manufacturing and fabricating due to increases in demand for flexible liners and improvements in technology.

It is important for the potential liner user to fully understand what materials are available in order to select the most cost-effective waste compatible liner. It is also important to fully appreciate all the physical and chemical conditions under which the liner will be used. For a liner to function successfully, the supporting structure or subgrade requires careful design based on the site conditions.

A successful liner is one which is able to maintain seepage at or below tolerable levels. Tolerable levels are based on the potential groundwater pollutants, the hydrogeology and the groundwater use/quality all of which are waste and site specific. Monitoring the integrety of the facility over time is an important part of the operation of an industrial waste impoundmemnt. A monitoring system and program must be carefully designed and operated in order to optimize the performance of the facility.

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APPENDIX A

Established standards by the National Sanitation Foundation (NSF, 1983) for the flexible liners addressed in this report.

LINER	PAGE
Unsupported Butyl Rubber	67
Unsupported Ethylene-Propylene Diene Terpolymer (EPDM)	68
Supported Thermoplastic EPDM	69
Unsupported Polychloroprene (Neoprene)	70
Unsupported Polyvinyl Chloride (PVC)	71
Unsupported Oil Resistant Polyvinyl Chloride (PVC-OR)	72
Unsupported High Density Polyethylene (HDPE)	73
Unsupported Chlorinated Polyethylene (CPE)	74
Supported Chlorinated Polyethylene (CPE)	75
Supported Chlorosulfonated Polyethylene (CSPE)	76

TABLE 3. MATERIAL PROPERTIES

BUTYL RUBBER (IIR)

Property	Test Method	Unsupported (U) 30	45	60
Gauge (nominal)	—	30	45	60
Thickness, mils minimum	ASTM D412	27	40.5	54
Specific Gravity	ASTM D792	1.20±.05	1.20±.05	1.20±.05
Minimum Tensile Properties (each direction)	ASTM D412			
1. Breaking Factor (pounds/inch width)		36.0	54.0	72.0
2. Elongation at Break (percent)		300	300	300
Tear Resistance (pounds, minimum)	ASTM D624 Die C	4	6	8
Low Temperature, °F	ASTM D746 Procedure B	-40	-40	-40
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	2	2	2
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
1. Breaking Factor		10	10	10
2. Elongation at Break		20	20	20
Water Absorption (percent change, maximum)	ASTM D471 158°F, 168 hours	2	2	2
Durometer A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 100 hours, 50 pphm 104°F, 20% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days at 240°F			
1. Elongation (percent, minimum)		210	210	210
2. Breaking Factor (pounds/inch width, minimum)		25.2	37.8	50.4
Factory Seam Requirements[1]				
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	28.8	43.2	57.6
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 6 lb/in	FTB[2] or 8 lb/in	FTB[2] or 10 lb/in
Dead Load				
Room Temperature 73°F 50% Bonded Seam Load	See Appendix A	Pass	Pass	Pass
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
Peel Adhesion		-20	-20	-20
Bonded Seam Strength		-20	-20	-20

---

[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tearing Bond

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 6. MATERIAL PROPERTIES

ETHYLENE-PROPYLENE DIENE TERPOLYMER (EPDM)

		Unsupported (U)		
Property	**Test Method**	**30**	**45**	**60**
Gauge (nominal)	—	30	45	60
Thickness, mils minimum	ASTM D412	27	40.5	54
Specific Gravity	ASTM D792	1.18±.03	1.18±.03	1.18±.03
Minimum Tensile Properties (each direction)	ASTM D412			
1. Breaking Factor (pounds/inch width)		42.0	63.0	84.0
2. Elongation at Break (percent)		300	300	300
Tear Resistance (pounds, minimum)	ASTM D624 Die C	4	6	8
Low Temperature, °F	ASTM D746 Procedure B	-55	-55	-55
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	2	2	2
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
1. Breaking Factor		10	10	10
2. Elongation at Break		20	20	20
Water Absorption (percent change, maximum)	ASTM D471 158°F, 168 hours	2	2	2
Durometer A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 7 days, 100 pphm 104°F, 50% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days at 240°F			
1. Elongation (percent, minimum)		210	210	210
2. Breaking Factor (pounds/inch width, minimum)		36.0	54.0	72.0
	Factory Seam Requirements[1]			
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	33.6	50.4	67.2
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 6 lb/in	FTB[2] or 8 lb/in	FTB[2] or 10 lb/in
Dead Load	See Appendix A			
Room Temperature 73°F 50% Bonded Seam Load		Pass	Pass	Pass
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
Peel Adhesion		-20	-20	-20
Bonded Seam Strength		-20	-20	-20

---

[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tear Bond

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 12. MATERIAL PROPERTIES

THERMOPLASTIC EPDM (T-EPDM)

Property	Test Method	Supported (S)	
		Type 1-30	Type 2-36
Gauge (nominal)	—	30	36
Thickness, mils minimum	ASTM D751		
1. Overall		27	33
2. Over Scrim	Optical Method (Reference Appendix A)	11	11
Breaking Strength (pounds, minimum)	ASTM D751 Method A	50[1]	100
Tear Strength (pounds, minimum)	ASTM D751 (As modified in Appendix A)		
1. Initial		10	25
2. After Aging		5	20
Low Temperature, °F	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-20	-20
Dimensional Stability (each direction percent change maximum)	ASTM D1204 212° F, 1 hr.	7.5	2
Volatile Loss (percent loss maximum)	ASTM D1203 Method A 30 mil sheet	0.5	0.5
Resistance to Soil Burial (percent change maximum in original values)	ASTM D3083 30 mil sheet (as modified in Appendix A)		
a. Unsupported Sheet			
1. Breaking Strength		10	10
2. Elongation at Break		20	20
3. Modulus at 100% Elongation		30	30
b. Membrane Fabric Breaking Strength	ASTM D751 Method A	25	25
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Procedure 1	80	160
Ozone Resistance	ASTM D1149 7 days, 100 pphm 104°F, ⅛ in. bent loop	No Cracks 7X	No Cracks 7X
Ply Adhesion (each direction pounds/in. width minimum)	ASTM D413 Machine Method Type A	8	8
	Factory Seam Requirements[2]		
Bonded Seam Strength (factory seam, breaking factor, lb, minimum)	ASTM D751 (as modified in Appendix A,	64	80
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	Ply sep in plane of scrim or 12 lb/in	Ply sep in plane of scrim or 12 lb/in
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)		
Peel Adhesion		-20	-20
Bonded Seam Strength		-25	-25

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[1] Type 1 liner has two values. Coating is stronger than fabric and gives breaking strength values of 80 pounds, with 150% minimum elongation.

[2] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 4. MATERIAL PROPERTIES

POLYCHLOROPRENE (CR)

		Unsupported (U)		
Property	Test Method	30	45	60
Gauge (nominal)	—	30	45	60
Thickness, mils minimum	ASTM D412	27	40.5	54
Specific Gravity	ASTM D297	1.48±.05	1.48±.05	1.48±.05
Minimum Tensile Properties (each direction)	ASTM D412			
1. Breaking Factor (pounds/inch width)		45.0	67.5	90.0
2. Elongation at Break (percent)		250	250	250
Tear Resistance (pounds, minimum)	ASTM D624 Die C	4	6	8
Low Temperature, °F	ASTM D746 Procedure B	-30	-30	-30
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	2	2	2
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
1. Breaking Factor		10	10	10
2. Elongation at Break		20	20	20
Water Absorption (percent change, maximum)	ASTM D471 158°F, 168 hours	12	12	12
Durometer A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 100 hours, 100 pphm 104°F, 20% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 70 hours at 212°F			
1. Elongation (percent, minimum)		150	150	150
2. Breaking Factor (pounds/inch width, minimum)		38.2	57.4	76.5
		Factory Seam Requirements[1]		
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	28.8	43.2	57.6
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 6 lb/in	FTB[2] or 8 lb/in	FTB[2] or 10 lb/in
Dead Load				
Room Temperature 73°F 50% Bonded Seam Load	See Appendix A	Pass	Pass	Pass
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)			
Peel Adhesion		-20	-20	-20
Bonded Seam Strength		-20	-20	-20

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[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tear Bond

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 1A. MATERIAL PROPERTIES POLYVINYL CHLORIDE (PVC)

		Unsupported (U)			
Property	**Test Method**	**10**	**20**	**30**	**45**
Gauge (Nominal)	—	10	20	30	45
Thickness, mils minimum	ASTM D1593 Para 8.1.3	9.3	19	28.5	42.75
Specific Gravity (minimum)	ASTM D792 Method A	1.20	1.20	1.20	1.20
Minimum Tensile Properties (each direction)	ASTM D882				
1. Breaking Factor (pounds/inch width)	Method A or B (1 inch wide)	23	46	69	104
2. Elongation at Break (percent)	Method A or B	250	300	300	300
3. Modulus (force) at 100% Elongation (pounds/inch width)	Method A or B	9	18	27	40
Tear Resistance (pounds, minimum)	ASTM D1004 Die C	3	6	8	11
Low Temperature, °F	ASTM D1790	-10	-15	-20	-20
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	5	5	5	5
Water Extraction (percent loss maximum)	ASTM D3083 (as modified in Appendix A)	-0.35	-0.35	-0.35	-0.35
Volatile Loss (percent loss maximum)	ASTM D1203 Method A	1.5	0.9	0.7	0.5
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)				
1. Breaking Factor		5	5	5	5
2. Elongation at Break		20	20	20	20
3. Modulus at 100% Elongation		20	20	20	20
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A	37	60	82	100
Factory Seam Requirements[1]					
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	18.4	36.8	55.2	83.2
Peel Adhesion (pounds/in. minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 10 lb/in	FTB[2] or 10 lb/in	FTB[2] or 10 lb/in	FTB[2] or 10 lb/in
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)				
Peel Adhesion		-20	-20	-20	-20
Bonded Seam Strength		-20	-20	-20	-20

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[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tearing Bond.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 1B. MATERIAL PROPERTIES

POLYVINYL CHLORIDE (PVC-OR)
OIL RESISTANT GRADE

Property	Test Method	Unsupported (U)
		30
Gauge (Nominal)	—	30
Thickness, mils minimum	ASTM D1593 Para 8.1.3	28.5
Specific Gravity (minimum)	ASTM D792 Method A	1.20
Minimum Tensile Properties (each direction)	ASTM D882	
1. Breaking Factor (pounds/inch width)	Method A or B (1 inch wide)	69
2. Elongation at Break (percent)	Method A or B	300
3. Modulus (force) at 100% Elongation (pounds/inch width)	Method A or B	27
Tear Resistance (pounds, minimum)	ASTM D1004 Die C	8
Low Temperature, °F	ASTM D1790	0
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	5
Water Extraction (percent loss maximum)	ASTM D3083 (as modified in Appendix A)	-0.35
Volatile Loss (percent loss maximum)	ASTM D1203 Method A	0.5
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)	
1. Breaking Factor		5
2. Elongation at Break		20
3. Modulus at 100% Elongation		20
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A	82

Oil Resistance Requirements

See ASTM D471, Oil Extraction, 7 days, percent maximum change, machine direction

	Neats Foot	Gulf Harmony #68	Corn (Mazola)	ASTM No. 2
Weight @73.4±3°F	- 5	- 5	- 5	- 5
Weight @158±3°F	- 15	- 15	- 15	- 10
Tensile @73.4±3°F	+5	+10	+10	+10
Tensile @ 158±3°F	+15	+15	+15	+15
Elongation @ 73.4±3°F	- 10	- 10	- 10	- 10
Elongation @ 158±3°F	- 25	- 15	- 25	- 25

Factory Seam Requirements[1]

Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	55.2
Peel Adhesion (pounds/in. minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 10 lb/in
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)	
Peel Adhesion		-20
Bonded Seam Strength		-20

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[1] Factory seam requirements are the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tearing Bond.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 5. MATERIAL PROPERTIES

HIGH DENSITY POLYETHYLENE (HDPE)

Property	Test Method	Unsupported (U) 80	 100
Gauge (nominal)	—	80	100
Thickness, mils minimum	ASTM D1593 Para. 8.1.3	72	90
Specific Gravity (minimum)	ASTM D792 Method A	0.930	0.930
Minimum Tensile Properties (each direction)	ASTM D638		
1. Tensile Strength Yield (lb/in width)		120	150
2. Tensile Strength at Break (lb/in width)		120	150
3. Elongation at Yield (percent)		10	10
4. Elongation at Break (percent)		500	500
5. Modulus of Elasticity (lb/sq in)		80,000	80,000
Tear Resistance (lb, minimum)	ASTM D1004 Die C	40	50
Low Temperature, ° F	ASTM D746 Procedure B	-40	-40
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	±3	±3
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)		
1. Tensile Strength Yield		10	10
2. Tensile Strength at Break		10	10
3. Elongation at Yield		10	10
4. Elongation at Break		10	10
5. Modulus of Elasticity		10	10
Environmental Stress Crack (minimum, hours)	ASTM D1693 (as modified in Appendix A)	500	500
		Factory and Field Seam Requirements[1]	
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	108	135
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	FTB[2]	FTB[2]
Dead Load			
Room Temperature 73°F 50% Bonded Seam Load	See Appendix A	Pass	Pass
Elevated Temperature 158°F 25% Bonded Seam Load	See Appendix A	Pass	Pass
Resistance to Soil Burial	ASTM D3083		
Peel Adhesion	(as modified in	FTB[2]	FTB[2]
Bonded Seam Strength (percent change maximum in original value)	Appendix A)	-20	-20

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[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tear Bond

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 2A. MATERIAL PROPERTIES

CHLORINATED POLYETHYLENE (CPE)

	Unsupported (U)		
Property	Test Method	20	30
Gauge (nominal)	—	20	30
Thickness, mils minimum	ASTM D1593 Para. 8.1.3	19	28.5
Specific Gravity (minimum)	ASTM D792 Method A	1.20	1.20
Minimum Tensile Properties (each direction)	ASTM D882		
1. Breaking Factor (pounds/inch width)	Method A or B	34	43
2. Elongation at Break (percent)	Method A or B	250	300
3. Modulus (force) at 100% elongation (pounds/inch width)	Method A or B	8	12
Tear Resistance (pounds, minimum)	ASTM D1004 Die C	3.5	4.5
Low Temperature, °F	ASTM D1790	-20	-20
Dimensional Stability (percent change maximum)	ASTM D1204 212°, 15 min.	16	16
Water Extraction (percent loss maximum)	ASTM D3083 (as modified in Appendix A)	-0.35	-0.35
Volatile Loss (percent loss maximum)	ASTM D1203 Method A	0.7	0.5
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)		
1. Breaking Factor		5	5
2. Elongation at Break		20	20
3. Modulus at 100% Elongation		20	20
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A	75	100
Factory Seam Requirements[1]			
Bonded Seam Strength (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	27	34
Peel Adhesion (lbs/in minimum)	ASTM D413 (as modified in Appendix A)	FTB[2] or 10 lb/in	FTB[2] or 10 lb/in
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)		
Peel Adhesion		-20	-20
Bonded Seam Strength		-20	-20

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[1] Factory bonded seam strength is the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

[2] FTB - Film Tear Bond

[3] Film Tearing Bond is acceptable.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 2B. MATERIAL PROPERTIES

CHLORINATED POLYETHYLENE (CPE)

		Supported (S)		
Property	**Test Method**	**2-30**	**3-36**	**3-45**
Gauge (nominal)	—	27	36	45
Thickness, mils minimum	ASTM D751			
1. Overall		32	34	41
2. Over Scrim	Optical Method (see Appendix A)	11	11	11
Breaking Strength (pounds, minimum)	ASTM D751	120	200	200
Tear Strength (pounds, minimum)	ASTM D751 (as modified in Appendix A)			
1. Initial		25	35	35
2. After Aging		20	25	25
Low Temperature, °F	ASTM D2136 ⅛ in. mandrel 4 hrs. Pass	-40	-40	-40
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 1 hr.	2	2	2
Volatile Loss (percent loss maximum)	ASTM D1203 Method A 30 mil sheet	0.5	0.5	0.5
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 30 mil sheet (as modified in Appendix A)			
a. Unsupported Sheet				
1. Breaking Strength		5	5	5
2. Elongation at Break		20	20	20
3. Modulus at 100% Elongation		20	20	20
b. Membrane Fabric Breaking Strength	ASTM D751 Method A	25	25	25
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Proc. 1	160	250	250
Ply Adhesion (each direction pounds/in. width minimum)	ASTM D413 machine method Type A	10	7	7
		Factory Seam Requirements[1]		
Bonded Seam Strength (factory seam, breaking strength, lbs min.)	ASTM D751 (as modified in Appendix A)	96	160	160
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	Ply sep in plane of scrim or 10 lbs./in.	Ply sep in plane of scrim or 10 lbs./in.	Ply sep in plane of scrim or 10 lbs./in.
Resistance to Soil Burial (percent change maximum in original value	ASTM D3083 (as modified in Appendix A)			
Peel Adhesion		-20	-20	-20
Bonded Seam Strength		-20	-20	-20

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[1] Factory seam requirements are the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

TABLE 10A. MATERIAL PROPERTIES CHLOROSULFONATED POLYETHYLENE (CSPE)

		Supported (S)					
Property	**Test Method**	**Type 1-30**	**Type 1-45**	**Type 2-36**	**Type 2-45**	**Type 3-36**	**Type 3-45**
Gauge (nominal)	—	30	45	36	45	36	45
Plies, Reinforcing	—	1	2	1	1	1	1
Thickness, mils minimum	ASTM D751						
1. Overall		27	41	32	41	34	41
2. Over Scrim	Optical Method (Reference Appendix A)	11	11	11	11	11	11
Breaking Strength-Fabric (pounds, minimum)	ASTM D751 Method A	60[1]	90[1]	120	125	200	200
Tear Strength (pounds, minimum)	ASTM D751 (As modified in Appendix A)						
1. Initial		10	16	25	30	60	70
2. After Aging		5	5	20	25	25	25
Low Temperature, °F	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-40	-40	-40	-40	-40	-40
Dimensional Stability (each direction percent change maximum)	ASTM D1204 212°F, 1 hr.	7.5	5	2	3	2	2
Volatile Loss (percent loss maximum)	ASTM D1203 Method A, 30 mil sheet	0.5	0.5	0.5	0.5	0.5	0.5
Resistance to Soil Burial (percent change maximum in original values)	ASTM D3083 30 mil sheet (as modified in Appendix A)						
a. Unsupported sheet							
1. Breaking Strength		5	5	5	5	5	5
2. Elongation at Break		20	20	20	20	20	20
3. Modulus at 100% Elongation		20	20	20	20	20	20
b. Membrane Fabric Breaking Strength	ASTM D751 Method A	25	25	25	25	25	25
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Procedure 1	80	140	160	180	250	250
Ply Adhesion (each direction pounds/in. width minimum)	ASTM D413 Machine Method Type A	10	10	10	10	7	7
		Factory Seam Requirements[2]					
Bonded Seam Strength (factory seam, breaking factor, lb, width)	ASTM D751 (as modified in Appendix A)	80	96	96	100	160	180
Peel Adhesion (lb/in minimum)	ASTM D413 (as modified in Appendix A)	Ply sep in plane of scrim or 10 lb/in	Ply sep in plane of scrim or 10 lb/in	Ply sep in plane of scrim or 10 lb/in	Ply sep in plane of scrim or 10 lb/in	Ply sep in plane of scrim or 10 lb/in	Ply sep in plane of scrim or 10 lb/in
Resistance to Soil Burial (percent change maximum in original value)	ASTM D3083 (as modified in Appendix A)						
Peel Adhesion		20	20	20	20	20	20
Bonded Seam Strength		-25	-25	-25	-25	-25	-25

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[1] Type 1 gauge liner has two values. Coating is stronger than fabric and gives a breaking strength value of 100 pounds for nominal 30 mil and 120 pounds for nominal 45 mils with 150% minimum elongation at break for both.

[2] Factory seam requirements are the responsibility of the fabricator. Factory seams are further discussed in Item 4.2.

This table provides a reliable and dependable means for industry to furnish such materials of known and consistent quality. Before selection of any material for an FML, however, the user should consult with appropriate manufacturers, because these materials may not be appropriate for every application. Specific information should be obtained from the manufacturers regarding installation requirements, exposure conditions, performance expectations, and experience factor.

APPENDIX B

SUMMARY OF THE GUIDELINES FOR CANADIAN DRINKING WATER QUALITY 1978

(Health and Welfare Canada, 1979)

Summary of the Guidelines for Canadian Drinking Water Quality 1978

Chemical and Physical	Parameter	Maximum Acceptable Concentration*	Objective Concentration*	Basis**
	Aldrin + Dieldrin	0.0007	5×10^{-8}	H
	Antimony	-	0.0002	H
	Arsenic	0.05	0.005	H
	Asbestos	-	-	-
	Barium	1.0	0.1	H
	Baron	5.0	0.01	H
	Cadmium	0.005	0.001	H
	Carbaryl	0.07	5×10^{-4}	H
	Chlordane (Total)	0.007	5×10^{-8}	H
	Chloride	250	250	A
	Chromium	0.05	0.0002	H
	Colour (TCU)	15	15	A
	Copper	1.0	1.0	A
	Cyanide	0.2	0.002	H
	DDT (Total)	0.03	5×10^{-8}	H
	Diazinon	0.014	1×10^{-6}	H
	Dieldrin + Aldrin	0.0007	5×10^{-8}	H
	Endrin	0.0002	5×10^{-8}	H
	Fluoride	1.5	1.0	H & A
	Hardness	-	-	-
	Heptachlor + Heptachlor Epoxide	0.003	5×10^{-8}	H
	Iron	0.3	0.05	A
	Lead	0.05	0.001	H
	Lindane	0.004	1×10^{-7}	H
	Manganese	0.05	0.01	A
	Mercury	0.001	0.002	H
	Methoxychlor	0.1	5×10^{-8}	H
	Methyl Parathion	0.007	1×10^{-6}	H
	Nitrate (as N)	10.0	0.001	H
	Nitrilotriacetic Acid (NTA)	0.05	0.0002	H
	Nitrate (as N)	1.0	0.001	H
	Odour	-	Inoffensive	A
	Parathion	0.035	1×10^{-6}	H
	Pesticides (Total)****	0.1	-	H
	pH	6.5-8.5	-	A
	Phenols	0.002	0.002	A
	Selenium	0.01	0.002	H
	Silver	0.05	0.005	H
	Sodium	-	-	-
	Sulphate	500	150	H & A
	Sulphide (as H_2S)	0.05	0.05	A
	Taste	-	Inoffensive	A
	Temperature (°C)	15	15	A
	Total Dissolved Solids	500	-	A
	Total Organic Carbon	-	-	-
	Toxaphene	0.005	5×10^{-8}	A
	Trihalomethanes	0.35	0.0005	H
	Turbidity (NTU)	5	1	H & A
	Uranium	0.02	0.001	H
	Zinc	5.0	5.0	A
	2,4-D	0.1	0.001	H
	2,4,5-TP	0.01	0.001	H

Biological	Parameter	Maximum Acceptable
	Coliform organisms	- 10 per 100 mL - 0 fecal coliforms - no more than 10% of the samples in a 30 day period shall show coliform presence

* Unless indicated otherwise, the maximum acceptable and objective concentrations are specified in mg/L.

** Maximum acceptable and objective concentrations have been established on the basis of either aesthetic (A) of health (H) considerations.

*** In areas where the annual mean maximum temperature is below 10°C, the objective is 1.2 mg/L.

**** The "total pesticides" limit applies to water in which more than one of the pesticides listed in this Table is present, in which case, the sum of their concentrations should not exceed 0.1 mg/L.

N.L.C. - B.N.C.
3 3286 06199272 9